SUPPLEMENTARY INVESTIGATIONS
OF
INFRA-RED SPECTRA

Part V—Infra-Red Reflection Spectra
Part VI—Infra-Red Transmission Spectra
Part VII—Infra-Red Emission Spectra

BY
WILLIAM W. COBLENTZ

WASHINGTON, D. C.
Published by The Carnegie Institution of Washington
1908

CARNEGIE INSTITUTION OF WASHINGTON

PUBLICATION NO. 97

The Plimpton Press Norwood Mass. U.S.A

CONTENTS.

PART VII. — INFRA-RED EMISSION SPECTRA. — *Continued.*

PREFATORY NOTE.

The present volume contains supplementary data on doubtful points, which arose in connection with the preceding work on infra-red spectra. The various phases treated, except Part VII, Chapter I, (4) and (5), and Chapter II, were ready for publication during the summer of 1907, when through the generosity of the Carnegie Institution of Washington it was made possible to combine all the material into a new volume, which was then delayed for the additional data on emission spectra of metal filaments and insulators, thus rounding up the subject as completely as is possible at this time. This completes, for the present, the "program of investigation." The subject, however, is not exhausted — not even thoroughly initiated — for we know but little more of the cause of absorption and of emission lines and bands, other than those due to several well-known groups of atoms, than we did twenty years ago, when Julius and Ångström, independently, examined infra-red spectra. Each renewed effort is a step in advance, as the present data on the effect of molecular weight illustrate. The main problem is to obtain suitable material, which seems to be partly a matter of chance. For example, one of the first substances ever examined for selective reflection was quartz. It is the easiest obtainable, and it illustrates the question of selective reflection better than any other substance yet found, save carborundum, which was one of the latest minerals to be examined. On the other hand, after examining over 300 different substances, it has remained until the very last to find a series that so well illustrates the effect of molecular weight as the data on the carbonates herewith presented. The reflection spectra of the carbonates and nitrates in solution deserve further study. They are easily obtainable, and their reflection bands, which are strong, lie in the region of the spectrum where the radiation is quite intense, so that no serious difficulty need be anticipated. Colloidal metals also deserve further attention. Artificial substances, except carborundum, have never been examined, and it is intended to make a study of the silicides, provided they can be melted into homogeneous masses.

In Part III (Carnegie Publication No. 65) the discussion of the accuracy attainable refers to the region up to about 12 μ. Beyond this point the absorption of the rock-salt prism increases very rapidly, and it was not possible to attain great accuracy. In fact, the writer has given but little weight to his isolated observations lying beyond 14 μ, although others have been able to verify them, a notable example being calcite (Carnegie

Publication No. 65, p. 70), where the probability of a band at 14 μ is based upon two spectrometer settings and only three observations.

In Carnegie Publication No. 65, Appendix V, "Note on Blowing Quartz Fibers," the originator of the method was then unknown to the writer. Since then it has been found that in addition to shooting quartz fibers the method of blowing them is fully described by Boys in the London Electrician, p. 220, Dec. 11, 1896, "Blowing and Shooting Quartz Fibers."

Prof. E. F. Nichols has written me that he found the method in 1891, and exhibited it at the jubilee celebration of the Physikalische Gesellschaft in Berlin in 1896.

In Carnegie Publication No. 35, p. 51, line 10 from the bottom should read: "Carbon dioxide is the only gas studied which has no strong absorption bands except at 4.5 μ and 14 μ."

W. W. COBLENTZ.

WASHINGTON, D. C., *May*, 1908.

PART V.

INFRA-RED REFLECTION SPECTRA.

CHAPTER I.

INTRODUCTION.

In the preceding volume, Part IV, the reflection spectra of several groups of chemically related minerals were examined, including sulphates, sulphides, and an extensive group of silicates. This examination did not include the oxides and carbonates which were not obtainable at that time. To examine the substances in chemically related groups seemed to be the only logical way to gain insight into the mechanism of selective absorption and of selective reflection. The main difficulty lay in obtaining material of sufficient size to produce a suitable reflecting surface. A list of minerals, which occur in sufficient size and homogeneity, was sent out to various mineral dealers who very kindly submitted several large boxes of specimens for selection. Even after this first elimination it was possible to obtain only about 10 per cent of the number of minerals desired. In addition to these minerals a considerable number of specimens were selected from the collection in the U. S. National Museum.

The apparatus and methods employed were essentially the same as in the preceding investigation. The spectrum was produced by means of a rock-salt prism, and mirror spectrometer previously described. The reflecting power of the mineral was compared with that of a silver mirror. The surfaces were ground plane, but were not always of the highest polish. Since primarily we are only concerned with the accurate location of bands of selective reflection, the question of polish is of secondary importance.

The spectrometer slits were 0.3 mm., or about 2′ of arc, as in the preceding work. The radiation from a Nernst "heater" was projected upon the reflecting surfaces by means of a mirror having a focal length of 15 cm. and an aperture of 12 cm.

The reflection spectrum was explored by means of a Rubens thermopile. Although its sensitiveness was greater than the radiometer used previously, the unsteadiness at times, due to magnetic disturbances, necessitated repeating the observations at each spectrometer setting. When using the radiometer, it was rarely necessary to repeat the observations in exploring the spectrum up to 9 or 10 μ, while in the present work, using a thermopile, the region beyond 9 μ was examined under the greatest difficulties, and in the case of the carbonates no attempt was made to locate the band at 11.4 μ. When the reflection faces were less than the standard size, 2 by 3 cm., which was frequently the case, the silver comparison mirror and the specimen were covered with diaphragms having equal openings, so that equal areas of the two surfaces were exposed.

CHAPTER II.

INFRA-RED REFLECTION SPECTRA OF VARIOUS SUBSTANCES.

CARBONATES.

SMITHSONITE ($ZnCO_3$).

(Stalactitic crystalline mass. From New Jersey. Curve *a*, fig. 1.)

The specimen examined was highly polished. The reflection curve is strong, and is a complex of two bands, as will be noticed in nearly all the carbonates examined. The maxima occur at 6.65 and 7.05 μ.

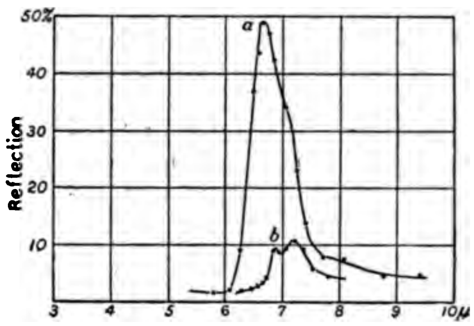


FIG. 1. — Smithsonite (*a*); Cerussite.

There seems to be a silicate calamine ($H_2O \cdot 2ZnO \cdot SiO_2$) having the same name. In fact the sample was purchased as a silicate. The present examination shows that the specimen examined is the carbonate known by that name. In other words, this is an independent method of analyzing such a mineral.

CERUSSITE ($PbCO_3$).

(From New South Wales. Curve *b*, figs. 1 and 2.)

This is a rare mineral and the present specimen was a fragment having a surface about 1.5 by 2 cm. The surface itself was corrugated, with several plain highly polished plates about 2 by 15 mm. It was the only specimen obtainable and no risk was taken in attempting to grind it. The reflection curve *b*, fig. 1, therefore does not indicate the true reflecting power. The individual bands, however, are well resolved, the maxima being at 6.9 and 7.25 μ. In fig. 2, curve *c*, the reflection curve is drawn on a larger scale, which emphasizes these maxima.

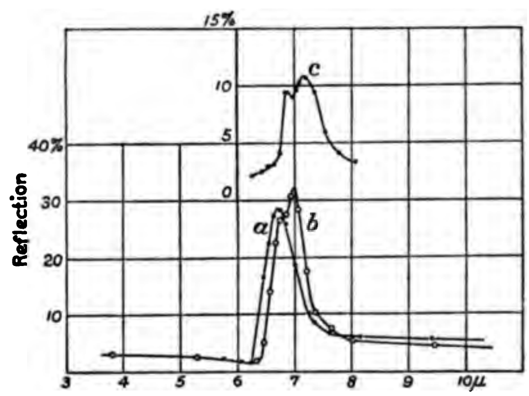


FIG. 2. — Strontianite (*a*); Witherite (*b*); Cerussite.

STRONTIANITE ($SrCO_3$).

(Massive specimen. From Hamm, Westphalia, Germany. Curve *a*, fig. 2.)

The specimen examined had a large, well-polished reflecting surface. As in all the carbonates studied the height of the maximum reflection is only about 30 per cent. This is the only carbonate examined which has but one reflection maximum, which is at 6.74 μ. It will be noticed presently that these maxima shift toward the long wave-lengths with increase in molecular weight. Since the intensity of the two bands is unequal, it is possible that this inequality, combined with the shift of the maxima, is the cause of the lack of resolution.

WITHERITE ($BaCO_3$).

(Massive, crystalline. Curve *b*, fig. 2.)

The reflection decreases normally from 4 to 6 μ followed by strong complex reflection band, with maxima at 6.78 and 6.98 μ. The latter band is the more intense, which is just the opposite of the carbonates, having a metal of less molecular weight. The specimen had an unusually high polish, which accounts, in part, for the high reflection maximum.

MALACHITE ($CuO \cdot CO_2 \cdot H_2O$).

(Concretionary specimen. From Burra Burra, South Australia. Curve *a*, fig. 3.)

The specimen of malachite was highly polished. The reflection bands are well resolved, while the second maximum is of the usual intensity for carbonates. Beyond 10 μ there appears to be another band, but the un-

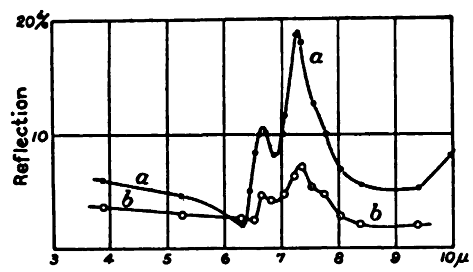


FIG. 3. — Malachite (*a*); Azurite.

steadiness of the galvanometer prevented an accurate determination of this question. The maxima of malachite occur at 6.66 and 7.3 μ, with a possible third band at 7.8 μ.

AZURITE ($3CuO \cdot 2CO_2 H_2O$): CHRYSOCOLLA ($CuSiO_3 + H_2O$).

(From Lyon County, Nevada. Curve *b*, fig. 3.)

The specimen examined was a mixture of azurite and chrysocolla, the first mineral being present in only a small amount. No silicate bands at

8.5 and 9 μ could be detected. The reflecting power is low, which is no doubt due to the presence of the silicate. The maxima at 6.65, 7.3, and 7.8 μ are in common with those of malachite. The transmission curve of azurite is given in the preceding volume. It shows the OH band at 3 μ and the carbonate bands at 3.5 and 4 μ.

DOLOMITE [$CaMg(CO_3)_2$].

(A plane cleavage piece. From Traversella, Italy. Curve *a*, fig. 4.)

Dolomite is of interest because it is a double carbonate of Mg and Ca. The reflecting power is high. The first band is in common with that of

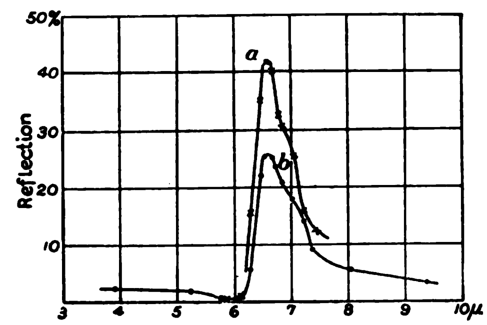


FIG. 4. — Dolomite (*a*); Siderite.

$CaCO_3$, while the second band is to be found in $MgCO_3$. The maxima occur at 6.58 and 6.95 μ.

SIDERITE ($FeCO_3$).

(Cleavage piece. From Allevard, France. Curve *b*, fig. 4.)

The reflection curve of siderite is composed of a complex maxima similar to that of dolomite. The maxima occur at 6.6 and 7.1 μ.

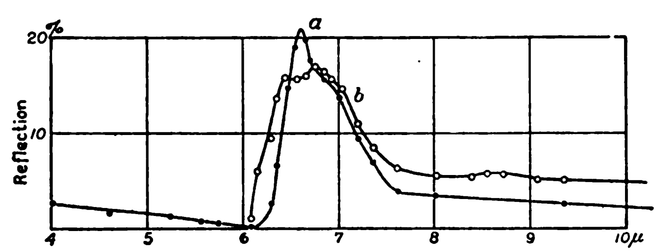


FIG. 5. — Calcite (*a*); Magnesite.

CALCITE ($CaCO_3$).

(Curve *a*, fig. 5.)

The reflection curve is obtained from a natural cleavage face of Iceland spar. The reflection band is complex with maxima at 6.6 and 6.85 μ. The reflection bands in the deep infra-red will be noticed presently. It is

desirable to examine aragonite, $CaCO_3$, which differs from calcite in its crystalline form, to determine the effect of structure; this is given in Chapter III. It was shown in Carnegie Publication No. 35 that isomeric compounds have different transmission spectra; and one would expect also the reflection spectra of isomers to be different. The unsteadiness of the galvanometer prevented the location of the band, found by Aschkinass, at 11.4 μ. In this region the radiometer would have been more satisfactory.

MAGNESITE ($MgCO_3$).

(Massive. Curve *b*, fig. 5.)

The sample examined was an opaque white mass which took a high polish. The band of selective reflection is very similar to that of calcite and consists of two maxima at 6.5 and 6.8 μ, respectively.

As a whole the carbonates are conspicuous for a double band of metallic reflection at 6.5 to 7 μ which previously had not been resolved in calcite. The shift of these bands with increase in molecular weight of the metallic ion will be discussed on a later page. That the shift is not due to a change in the adjustment of the apparatus was verified at the completion of the observations by examining several of the specimens in succession, when it was found that the maxima coincided with the values first observed.

SULPHIDES.

The reflection spectra of sulphur and of the sulphides of Zn, Sb, Fe, and Pb were described in the preceding volume. Sulphur and sphalerite (ZnS) have a low reflecting power of only about 8 per cent throughout the spectrum to 15 μ. The remaining minerals have a high reflecting power of 32 to 36 per cent throughout the spectrum to 15 μ, where the reflection of stibnite, Sb_2S_3, seemed to decrease. The present examination includes four new sulphides.

MOLYBDENITE (MoS).

(Massive foliated. From South Australia. Curve *a*, fig. 6.)

This mineral is very soft, like graphite. The specimens were folded and distorted so that it was not possible to grind a surface parallel to a cleavage plane. The surface took a high polish, but no luster as is found in the cleavage lamina. The reflection curve is fairly uniform beyond 4 μ, which would indicate that the lack of polish had no serious effect beyond this point. The reflecting power is low and uniform (18 to 20 per cent, as compared with stibnite, 35 per cent) throughout the spectrum to 14 μ, which is to be expected from its electrical conductivity. (For further references to electrical conductivity, etc., see Carnegie Publication No. 65, p. 93; also Königsberger, Jahrb. Radioaktivität & Elektronik, vol. 4, p. 161, 1907.)

PYRRHOTITE [(Fe, Ni)S].

(Massive. From Sudbury, Ontario. Curve *b*, fig. 6.)

The specimen examined did not appear so highly polished as molybdenite. It is composed of a bright metal and a darker background. The reflecting power is higher than that of MoS, and increases rapidly with wave-length through the spectrum of 14 μ.

CHALCOCITE (Cu_2S).

(Curve *c*, fig. 6.)

The reflecting power rises rapidly from 15 per cent at 1 μ to 45 per cent at 4 μ, while beyond 7 μ the reflecting power has a fairly constant

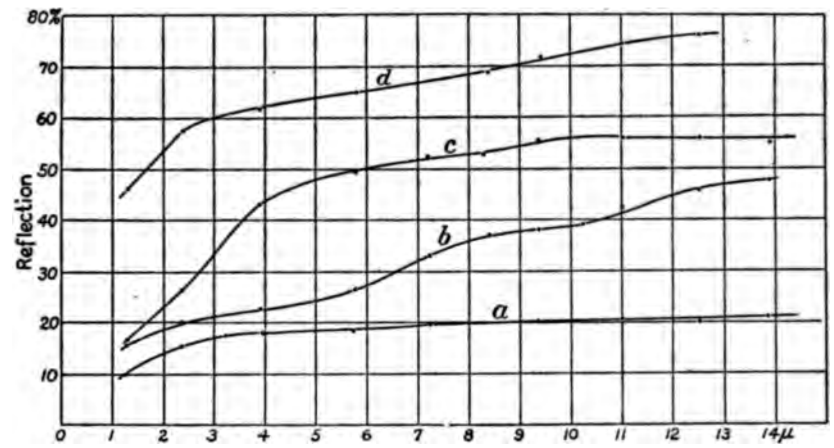


FIG. 6. — Molybdenite (*a*); Pyrrhotite (*b*); Chalcocite (*c*); Covellite.

value of 55 per cent. This substance is black, not unlike magnetite and the Siberian graphite previously described. The polish was higher than in pyrrhotite.

COVELLITE (CuS).

(From Anaconda Mine, Butte, Montana. Curve *d*, fig. 6.)

This mineral is of a steel-blue color, and appears as compact as steel. The reflecting power rises rapidly at 1 and 2 μ and then more slowly to 14 μ, where it amounts to 75 per cent.

As a whole, the examination of the sulphides shows that the sulphur atom has merely reduced the reflecting power of the metal, but has not brought about any bands of selective reflection in the region examined. In the case of sphalerite (ZnS) the sulphur atom has introduced into the metal a property which is to be found only in non-metals, viz, low reflecting power and selective absorption in the infra-red. Of the elements which are on the border line between metals and non-metals, selenium behaves like a metal in its high reflecting power (see fig. 7) and absence of infra-red absorption bands, while iodine and sulphur (non-metals) have absorption bands in this region.

SELENIUM (Se).

(Curve *d*, fig. 7.)

Selenium has practically the same reflecting power (18 to 20 per cent) as molybdenite. Pfund (Johns Hopkins Univ. Circular No. 4, 1907) has made a thorough investigation of the infra-red polarization of this substance.

OXIDES.

In the previous examination only quartz (SiO_2) represented this important group of minerals.

MAGNETITE (Fe_3O_4).

(From Port Henry, Essex County New York. Curve *a*, fig. 7.)

The surface examined was a triangular crystal, face about 3 cm. on an edge. The specimen was very homogeneous, but did not take a high polish, sufficient to observe the reflected image of an object at a small angle of incidence. The reflecting power rises uniformly throughout the spectrum, showing that the observations are affected by the lack of polish.

HEMATITE (Fe_2O_3).

(From Cumberland, England. Curve *b*, fig. 7.)

The specimen examined was a very dense homogeneous concretion, polished parallel to the radius of growth. The surface had a high polish (better than that of magnetite), reflecting a strong image of a source at a

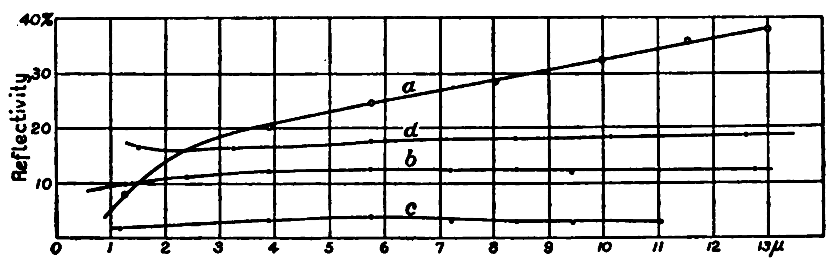


FIG. 7.—Magnetite (*a*); Hematite (*b*); Chromite (*c*); Selenium.

small angle of incidence. The reflecting power, in the infra-red, is far below that of magnetite, although it is higher in the visible. The reflecting power is uniformly 12 per cent, from which it would appear that this is the normal value for hematite.

CHROMITE (FeO, Cr_2O_3).

(From Lancaster County, Pennsylvania. Curve *c*, fig. 7.)

The surface of this dark specimen was mottled, parts of which took a high polish. The reflecting power is uniformly 4 per cent throughout the spectrum.

It is of interest to note that the iron oxides show no bands of selective reflection in the region of the spectrum up to 15 μ; zincite, ZnO, fig. 9, is another example.

Scheelite ($CaWO_4$).

(Massive. From Armidale, New South Wales. Curve *a*, fig. 8.)

The reflection power of this mineral behaves in the usual manner, being low in the region of the spectrum up to 11 μ, followed by a strong complex band of selective reflection, the maximum of which extends from 11.3 to 12.5 μ, the possible single maxima being at 11.3, 11.8, and 12.4 μ. The reflecting power is unusually low on the long wave-length side of the reflection band.

Zircon ($ZrSiO_4$).

(Near Eganville, Renfrew County, Ontario. Curve *b*, fig. 8.)

The specimen examined was a large rectangular cleavage piece, about 3 by 3 cm., of brownish color, semitransparent in thin sections.

Although this is a double oxide of zircon and silicon, the reflection curve is entirely different from the silicates previously studied. The strong band of selective reflection occurs farther toward the long wave-lengths, the single maxima (not well resolved) being at 10.1, 10.6, and 11 with a pos-

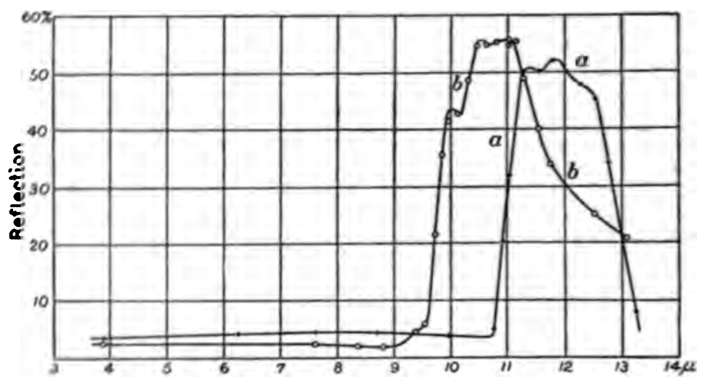


Fig. 8. — Scheelite (*a*); Zircon.

sible band at 11.7 μ. As a whole the reflection curve is exactly the same as that of willemite, Zn_2SiO_4, previously studied. In the latter, the bands are well resolved and occur at 10.1, 10.6, 11.0, and 11.6 μ. From this it would appear that in these two minerals the effect of SiO_2 is different from that found in quartz and in the minerals commonly known as silicates, viz, silicates of Ca, Mg, Fe, etc. Some of the latter, however, have the last band lying close to the first band in the present silicates.

Wulfenite ($PbMoO_4$).

(Red Cloud Mine, Yuma County, Arizona. Curve *a*, fig. 9.)

This is a chrome-red crystal. A natural crystal face, 1.5 by 2 cm., having a high polish, but not perfectly plane, was examined. In spite of this the reflection curve is one of the most remarkable yet found. The band of metallic reflection is almost as strong as quartz. There are two

maxima, at 11.75 and 13.1 μ, respectively. The reflecting power decreases uniformly from 12 per cent at 4 μ to 10 per cent at 8 μ, passes through a minimum of 4 per cent at 10.8 μ, then suddenly rises to 78 per cent at 11.75 μ.

Rutile (TiO_2).

(Graves Mountain, Lincoln County, Georgia. Curve *b*, fig. 9.)

The surface of the specimen examined was a natural crystal face, area about 1.4 by 1.8 cm., having a high polish, but uneven and containing cracks.

The reflection curve is the most unusual of all examined in that the band of selective reflection occurs almost at the working limit of a rock-salt prism. The maximum is broad and is fairly well defined at 13.6 μ.

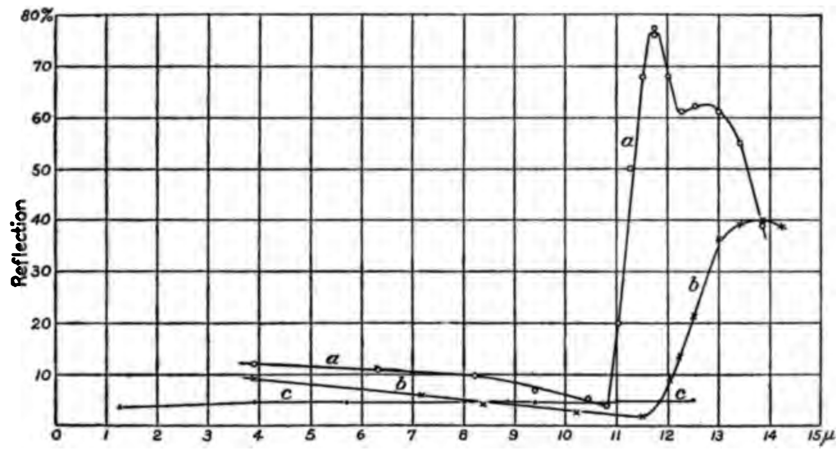


Fig. 9.—Wulfenite (*a*); Rutile (*b*); Zincite.

Zincite (ZnO).

(From Franklin, New Jersey. Curve *c*, fig. 9.)

The specimen examined was massive, having a red color and a dull polish. The surface was full of cracks, which would materially reduce the reflecting power. The reflecting power is low and uniform throughout the region of the spectrum examined. No bands of selective reflection were found. In this respect zincite is similar to iron oxide, but, on account of its low reflecting power, it is to be classed with the "insulators," and hence one would expect to find bands of selective reflection in the infra-red.

Corundum (Al_2O_3).

(Craigmont, Renfrew County, Ontario. Curve *b*, fig. 10.)

This specimen was an opaque crystal, of which a cleavage surface, about 2 by 3 cm. in area, was examined. The surface contained striæ, but otherwise had a high polish. The reflecting power is unusually low, except in the region of selective reflection, when it is quite high. The region of selective reflection is wide with maxima at 11.0, 11.8, and 13.5 μ.

ALUMINUM SILICATES.

There is no special reason for thus classifying the following minerals, except that most of them are quite unlike the commoner silicates previously examined.

CYANITE ($Al_2O_3SiO_2$).

(Yancy County, North Carolina. Curve *a*, fig. 10.)

The color of this flat crystal was light green. The flat crystal face, 2.5 by 3.5 cm., was ground but did not have a high polish. The band of selective reflection has three sharp maxima, at 9.3, 9.78, and 10.28 μ,

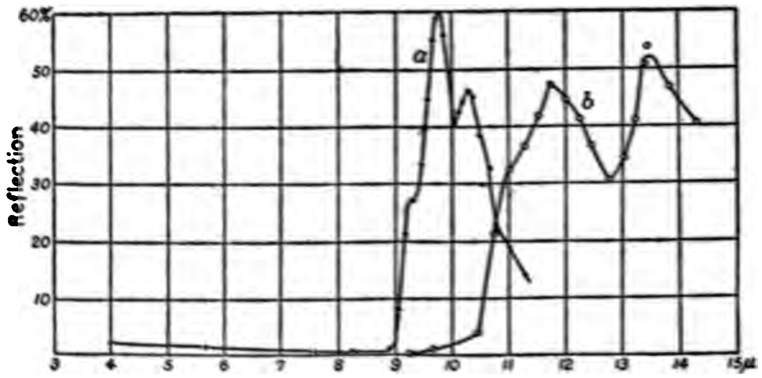


FIG. 10. — Cyanite (*a*); Corundum.

respectively, and is not unlike that of willemite (Zn_2SiO_4), except that in the latter the whole band is shifted to longer wave-lengths with the maxima at 10.1, 10.6, and 11 μ.

BERYL [$Be_3Al_2(SiO_3)_6$].

(From North Carolina. Fig. 11.)

The surface examined was ground on a crystal face. The specimen was opaque and green in color. The reflection curve follows the usual course with a band of selective reflection extending from 8 to 10.5 μ. The

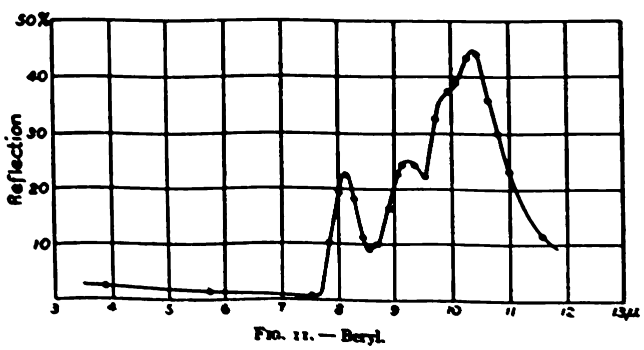


FIG. 11. — Beryl.

maxima are not so high as usual with silicates, but they are sharp and occur at 8.15, 9.2, 9.9, and 10.4 μ.

TOPAZ [$(Al, F)_2SiO_4$].

(Villa Rica Mines, Geraes, Brazil. Curves *a* and *b*, fig. 12.)

The specimen from Brazil was a yellow rectangular prism with faces 1 by 2.5 cm. The natural face, which had a high polish, was examined. The reflection curve *a*, fig. 11, is low throughout the spectrum, except in

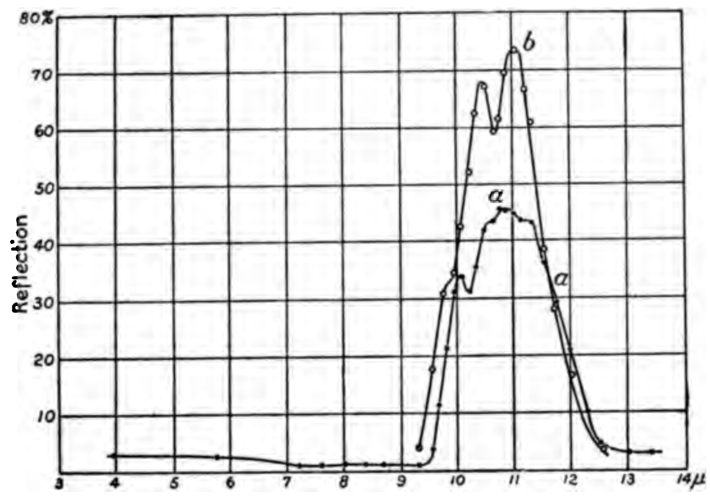


FIG. 12. — Topaz.

the region of selective reflection, which extends from 10 to 11.5 μ with unresolved maxima at 10.05, 10.6, 10.9, and 11.3 μ.

The white topaz examined, curve *b*, fig. 11 (in its highest part), is an almost exact reproduction of the quartz curve, with the exception that the latter is shifted to the longer wave-lengths. The white topaz, which was ground and had a fairly high polish, has sharp maxima at 9.9, 10.45, and 11 μ with a possible band at 12 μ. The band at 11 μ is in common with that of several other silicates.

SODIUM SILICATE (Na_2SiO_3).

(Curve *b*, fig. 13.)

The curve of liquid glass is similar to that of the glasses previously examined. This is one of the simplest obtainable chemical compounds of the silicates, and is further evidence that the silicon oxide radical is not so constant in its behavior toward heat-waves as was found in the CO_2 radical of the carbonates.

SPODUMENE [$LiAl(SiO_3)_2$].

(From Pennington County, South Dakota. Curve *a*, fig. 13.)

This mineral is of the same composition as kuntzite, the transmission curve of which is given on a later page. The specimen examined was a polished cleavage piece from a large gray crystal. The maxima of the selective reflection bands occur at 9.18, 9.7, and 10.4 μ, respectively.

In conclusion, it may be said that, from all of the silicates examined, there is no regularity in the position of the maxima such as obtains in the sulphates and the carbonates. It is true that in a few cases the maxima are in common, but, on the whole, the evidence indicates that there is no uniform group of atoms acting in common as is found in the sulphates and carbonates. In other words, the silicon radical is different in the

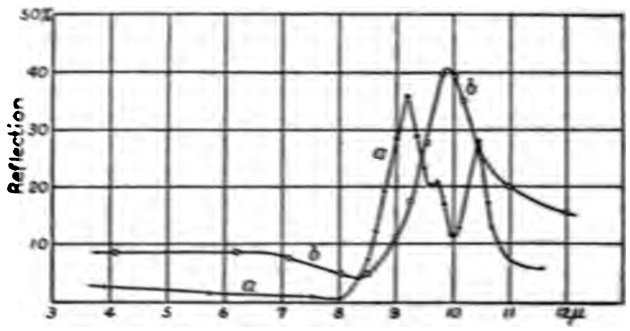


Fig. 13. — Spodumene (a); Sodium silicate.

different minerals. This seems to be the necessary interpretation to be given, for it has been impossible to work out a relation with the molecular weight of the molecule, such as exists in the carbonates and sulphates, to be discussed on a later page.

CHAPTER III.

MINUTE EXAMINATION OF THE REFLECTION BANDS OF QUARTZ AND OF THE CARBONATES.

Having assembled a fluorite prism and bolometer for radiation work, it seemed worth while to spend some time on the examination of the reflection bands at 6 to 7 μ in the carbonates, and at 8.5 to 9 μ in quartz. The fluorite prism had a circular aperture of 3.3 cm., angle 60°, and was perfectly clear. It was mounted on the spectrometer used in the previous work and, for the regions of the spectrum examined, the dispersion was from 4 to 6 times that of rock salt. On account of the large dispersion and the small prism face, the deflections were only about one-tenth that previously used. The glower of the Nernst lamp was used in order to obtain a sufficiently strong source of radiation. The main objection in using a glower is its narrowness, which requires greater care in maintaining a constant adjustment. The bolometer strip was about 0.5 mm. or 4′ of arc, while the temperature sensibility was 1 mm. $= 5^\circ \times 10^{-6}$C. A radiometer would have been more satisfactory, but the bolometer was conveniently at hand. With this greater dispersion it was found that the reflection bands of some of the carbonates are quite complex, while in others there is but one band.

QUARTZ.[1]

(Crystal cut perpendicular to optic axis. Curve *b*, perfectly clear specimen of quartz glass, fig. 14.)

It has repeatedly been noticed that the various silicates have quite different reflection spectra, while in the carbonates and in the sulphates the spectra show great similarity. It was therefore assumed that the silicon oxide radical is differently united in the different silicates. All the evidence obtainable, without exception, of substances in the solid or liquid (crystalline or amorphous) condition, shows that crystallographic form does not explain these anomalies; neither will the slight impurities present in many of the silicates explain them.

Pfund[2] found identical reflection bands of sodium-potassium tartrate ($C_8H_4K\ NaO_6 + 4H_2O$) in the form of a polished crystal, and also in the molten condition. His reflection maxima of molten nitroso-dimethylani-

---

[1] The writer is indebted to Dr. Day and Mr. Sheppard, of the Geophysical Laboratory of the Carnegie Institution of Washington, for the sample of quartz glass.

[2] Pfund, Astrophys. Jour., 24, p. 31, 1906.

line [$(CH_3)_2NC_6H_4NO$] coincide with the absorption maxima found by the writer for a solid film of this compound. Furthermore, the writer found that reflection spectra of solids in solution may or may not be identical with that of the solid, noteworthy examples being the sulphates of copper and of sodium. The cause of the reflection bands is therefore to be sought within the molecule.

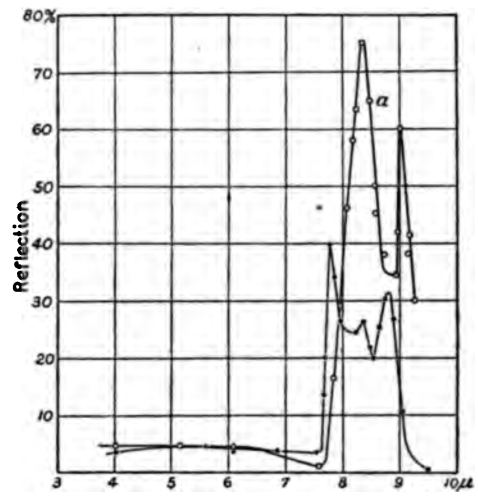


Fig. 14. — Quartz: (a) Crystalline; (b) Amorphous.

From the fact that the physical and chemical properties of quartz-glass are different from the crystal, one would infer that there is a difference in the molecular structure. This is well illustrated in fig. 14. The reflection spectrum of the amorphous material is entirely different from that of the crystal. It seems to have no connection with any of the silicates examined. The maxima of the reflection spectrum of crystalline quartz occur at 8.4 and 9.02 μ, while those of the amorphous quartz are found at 7.8, 8.4, and 8.8 μ, respectively. The intensity of the maxima of bands of the amorphous quartz is not so great, neither does the reflecting power, in the region of the spectrum just preceding a reflection band, fall to so low a value as in crystalline quartz.

In this connection it may be noticed that the various kinds of glass (sodium silicates) previously examined have similar reflection spectra.

Calcite and Aragonite ($CaCO_3$).

(Fig. 15. Curve *a*, calcite; curve *b*, aragonite.)

From the fact that, although the carbonates examined belong to only two crystal systems,[1] the reflection spectra are different, one would infer that the cause is not to be attributed to crystalline form. Previous examinations have shown that isomeric substances have different spectra. One would therefore expect to find the spectra of calcite and aragonite to be different, as was previously found for orthoclase and microclene ($KAlSi_3O_8$) at 8 to 10 μ. The fact that the substances are inorganic, and that the reflection bands are far in the infra-red, is of interest but non-essential.

In fig. 15, curve *a* gives the reflection from the plane, highly polished

[1] To the *rhombohedral* system belong $CaCO_3$ (calcite), $MgCO_3$, $FeCO_3$, and $ZnCO_3$; to the *orthorhombic* system belong $CaCO_3$ (aragonite), $BaCO_3$, $SrCO_3$, and $PbCO_3$. In the former group the band toward the shorter wave-length appears to be the most intense, while in the latter group the bands seem sharper and of more uniform intensity.

cleavage face of Iceland spar. With the larger dispersion the band previously found at 6.6 μ is now resolved into two bands with maxima at 6.5 and 6.6 μ, respectively. The region at 7 μ is evidently still more complex, but not resolved even with this greater dispersion. In curve *b* is given the reflection spectrum of a clear crystal of aragonite. The crystal face was small, only about 6 by 15 mm., and since the area of the comparison mirror was not reduced in like proportion, the reflecting power of the maxima is really higher than here given. In fact, for a well-polished crystal the reflecting power is no doubt as high as for calcite. The important point of interest in the present examination is that aragonite has only two reflection maxima, of about equal intensity, and located at 6.53 and 6.75 μ, respectively.

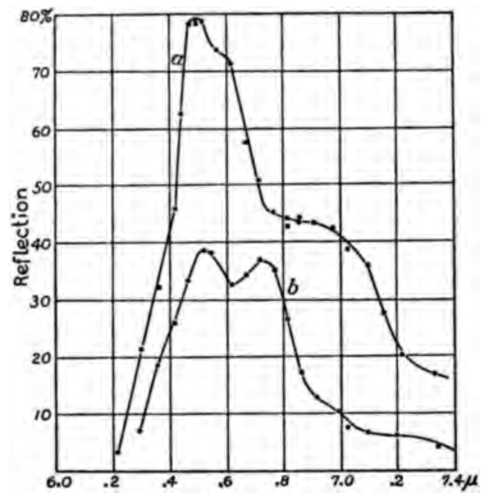


FIG. 15. — Calcite (*a*); Aragonite.

MAGNESITE ($MgCO_3$).

(Curve *a*, fig. 16.)

This sample was previously examined (fig. 5). In the present curve there are three bands with maxima at 6.42, 6.65, and 6.9 μ.

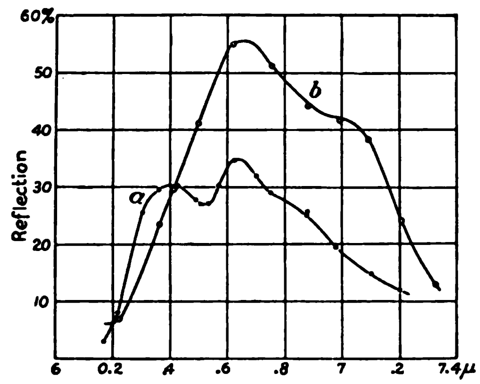


FIG. 16. — Magnesite (*a*); Smithsonite.

SMITHSONITE ($ZnCO_3$).

(Curve *b*, fig. 16.)

This sample was previously examined (fig. 1), when two maxima were found. In the present examination the bands are more resolved, but the maxima occur at 6.65 and 7.05 μ, respectively, as in the previous investigation.

STRONTIANITE ($SrCO_3$).

(Curve *a*, fig. 17.)

The band at 6.68 μ is not resolved even with the large dispersion of fluorite. The band is symmetrical, as previously found in fig. 2.

WITHERITE ($BaCO_3$).

(Curve *b*, fig. 17.)

The pair of bands is somewhat better resolved, with maxima at 6.7 and 6.97 μ, respectively, the same as was found in the previous examination of this same specimen (see fig. 2). The reflecting power is slightly lower

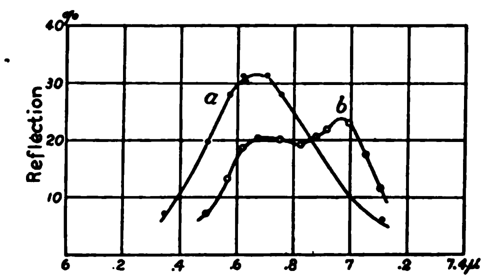


FIG. 17. — Strontianite (*a*); Witherite.

but that is to be attributed to the difference in the adjustment, *i.e.*, the faces of the comparison mirror and of the substance may not have been in the same plane. As a result they would not reflect the same part of the image of the glower upon the spectrometer slit. This is of minor importance since we are not concerned with the absolute reflecting power.

On a subsequent page it is shown that an emission band of Adularia occurring at 2.9 μ is shifted to 3.2 μ in the absorption spectrum of the crystalline material. Using polarized energy, the reflection bands of the carbonates depend upon the direction of vibration of the incident energy. The author therefore hopes to investigate water solutions to learn the behavior of these reflection bands, using polarized radiation.

CHAPTER IV.

REFLECTION SPECTRA IN THE EXTREME INFRA-RED.

From the foregoing work on selective reflection in which a single reflecting surface was used, it is apparent that by successive reflection of heat-waves from several surfaces there will remain only the residual rays lying in the region of selective reflection. It was noticed that the reflecting power in the region of 4 to 8 μ is only about $\frac{1}{10}$ that of the band of selective reflection. Hence, after reflecting from three surfaces the intensity would be only $\frac{1}{1000}$, and after five reflections only $\frac{1}{100000}$.

Rubens and Nichols[1] were the first to apply this method in locating the maxima of the residual rays of a series of substances including quartz, mica, fluorite, rock-salt, sylvite, crown and flint glass, sulphur, alum, and calcite. By using a grating of fine wire they were able to extend their observations to 61 μ, the longest heat-waves yet identified. Of the above-mentioned substances, only the first four were found to have bands of residual rays in the extreme infra-red.

Aschkinass[2] did some further work on this subject, examining marble, calcite, selenite, alum, sodium bromide, and potassium bromide. He found a band of residual rays at 29.4 μ in marble, and showed that similar bands exist in the bromides, the maxima of which lie beyond 60 μ.

From the results obtained with the silicates (see Carnegie Publication No. 65, pp. 80 to 90), especially glass, it becomes apparent that one can hardly expect to locate bands of residual rays in the extreme infra-red, even at 18 to 20 μ, unless they are much more intense than those found in the region of 8 to 10 μ. For it is necessary to have several reflecting surfaces to eliminate the large amount of energy of short wave-lengths as compared with the small amount to be measured, of the long wave-lengths. As is well known now, in the case of quartz, rock-salt, and sylvite, this is an easy matter on account of the high reflecting power of these bands. For example, for the band at 61 μ, which was examined after reflection from five surfaces of sylvite, it was found that the reflecting power of sylvite is 80 per cent. The galvanometer deflections were only about 5 mm. in the maximum of the band. If the reflecting power were only one-half this amount (*cf.* the silicates), the galvanometer deflection after five reflections would be one thirty-second of 5 mm., which could not be

[1] Rubens and Nichols, Ann. der Phys. (3), 60, p. 418, 1897.

[2] Aschkinass, Ann. der Phys. (4), 1, p. 42, 1900.

observed with accuracy. In the case of the silicates (as compared with quartz), where the height of the reflection band at 8 to 10 μ is always considerably less than 50 per cent, after three reflections the galvanometer deflections would be only 1 or 2 mm. at 18 to 20 μ. It does not follow, therefore, because no residual rays of a substance are to be found in the region of 18 to 20 μ, as was the case in the present examination, that no bands exist, but that they are too weak to be measured. From the similarity of the spectra, throughout the infra-red, of great groups of chemically related compounds, and from the fact that quartz and mica have bands of residual rays in the region of 18 to 20 μ, it is to be assumed that the silicates, in general, are selectively reflecting in this region. The fact that no bands were found is to be attributed to the weakness of the reflection bands.

As a whole, however, the reflecting power of some of these bands is very high. One has really no conception of the state of affairs until he examines a substance like quartz. The phenomenon is so easily observed with quartz that it might well serve as a general laboratory experiment. In regard to the ease of observing in the infra-red, the writer's experience has extended from the optical region into the most remote infra-red, and it may be said that more difficulty was experienced in the region of 12 to 15 μ, on account of the absorption of the rock-salt prism, than in the region of greater wave-lengths. The actual intensity in the emission spectrum differs greatly throughout the spectrum. For example, Rubens and Aschkinass (*loc. cit.*) compute that for a temperature of 2000° the maximum emission at 1.5 μ is 800,000 times as great as at 60 μ.

APPARATUS AND METHODS.

In the present examination the usual methods of procedure were employed. The spectrometer was the one used in previous work. The spectrum was produced by means of a wire grating *G*, fig. 18. The grating was made by the well-known method of winding two copper wires of the same diameter on a brass frame. One wire was then unwound and the remaining one was fastened to the frame by means of an electrolytic deposit of copper. The strands were then cut from one side of the frame. The wire was not of uniform thickness, so that the grating was far from perfect. Such a grating has the well-known property of producing only the odd order of spectra. On account of its imperfections it was not possible to make accurate measurements on orders higher than the seventh, using a Bunsen sodium flame. Two gratings were employed, the one (No. 2) having a constant of $K=0.2120$ mm., for the other $k=0.3279$ mm., determined with the sodium flame. The coarser grating was the more uniform in its individual windings, but in one region the wires were more closely but very regularly wound. The magnesite band at 29.4 μ was apparently double, at least very wide, just as though this grating spectrum

contained "ghosts." For the main part of the investigation grating No. 2 was used, which on account of the finer wires was not so regular in its winding. Using three reflections from quartz it was possible to observe the third order maximum of the band of wave-length, 9.05 μ; in all other cases, the third order spectrum was too weak for observation. A grating having wires of more uniform diameter and more uniformly wound, *e.g.*, wound on a screw thread, would no doubt have been more efficient in producing a pure spectrum.

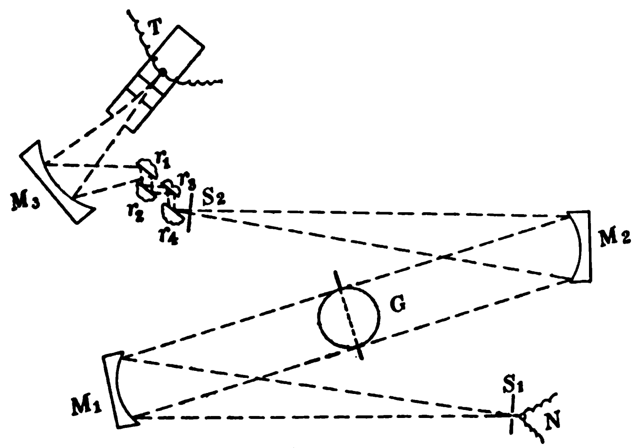


FIG. 18.

The spectrometer arm carrying the Nernst "heater," the slit S_1 and the mirror, m_1, was movable. The plane of the grating was made normal to the beam of light by placing a mirror on the wires and revolving the grating until an image of the slit, S_1, was projected back upon the slit. It was not convenient to have the collimating mirror and the grating revolve about the spectrometer axis, which is necessary to maintain the same grating constant. Accordingly the grating was kept in a fixed position and the spectrometer arm, carrying the mirror and source, was revolved about it.

The apparatus was calibrated by locating the maxima of the selective reflection bands of substances previously examined by Rubens and Nichols and by Aschkinass, viz, quartz at 8.7 and 20.75 μ, mica at 18.4 and 21.25 μ, fluorite at 24.4 μ, and calcite at 29.4 μ. The calibration curves are shown in fig. 19, where curve *a* is for the grating having a constant $K=0.3279$ mm. (for Na), and curve *b* is for the grating (No. 2) having a constant $K=0.2120$ mm. (for Na). In this curve the abscissæ are the maxima of reflection bands and the ordinates are the rotations of the spectrometer arm from the zero position. Blocks of wood with vertical metal plates, having openings 2 by 3 to 4 by 5 cm. were mounted securely upon a board, as shown at r_1, r_2, r_3, r_4. The minerals were secured to the back of the metal

plates by means of soft wax, the plane faces being, of course, placed over the openings in the plates. In case less than four reflecting surfaces were available, aluminum mirrors were placed in the remaining holders. A short focus mirror projected an image of the slit, S_2, upon an improved iron-constantan thermopile of 20 junctions. The wire used in the thermopile was only 0.075 mm. in diameter. This eliminated heat conduction and there was no drift of the zero. The galvanometer suspension weighed about 10 mg., which eliminated the effect of earth tremors. This, however, necessitated lengthening the period to gain great sensitiveness. The

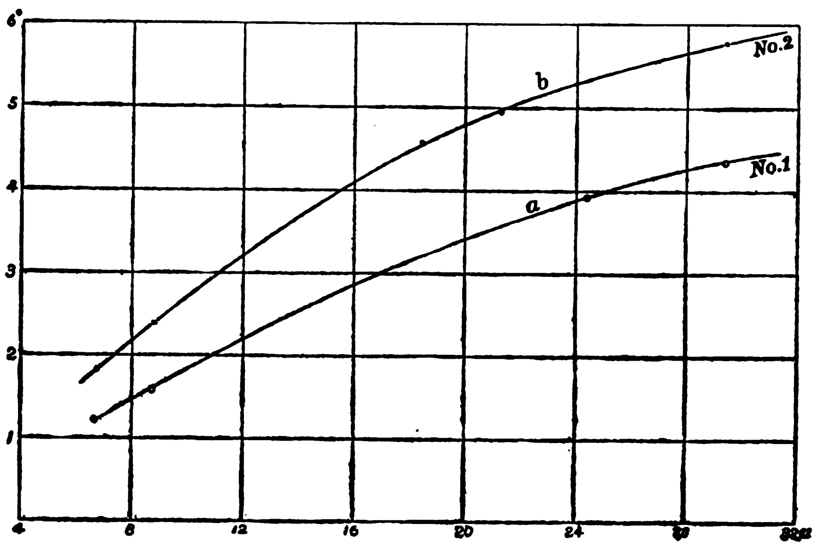


FIG. 19.— Wire-grating calibration.

thermopile was in a metal case, wrapped in felt, and the complete outfit was perfectly steady. It was, therefore, possible to increase the period of the galvanometer to 20 to 30 seconds (single swing) when its sensitiveness was $i=5\times10^{-11}$ ampere on a scale at 1 m. The resistance of the thermopile was 8.9 ohms. The galvanometer resistance was 5 ohms, from which it was computed that a deflection of 1 mm. $=7\times10^{-7}$ °C. for a scale at 1 m.

From this it will be seen that the temperature sensitiveness of the instrument was as great as, and in some instances greater than, in previous investigations. Hence, it appears that in numerous cases the absence of reflection bands is to be attributed to some property in the material rather than to a fault in the instruments.

The whole apparatus was, of course, thoroughly protected from stray light by providing numerous black pasteboard screens.

RESIDUAL RAYS[1] FROM MICA.

MUSCOVITE MICA [$H_2KAl(SiO_4)_3$].

In fig. 20 are plotted the spectrometer arm rotations (abscissæ) and the galvanometer deflections in the grating spectrum of mica. The sharp maximum at A is the central image, while B_1 is the selective reflection band (first-order spectrum) in the region of 9 μ. For this part of the curve three reflection surfaces were used, while to obtain the part C_1, C_2 four reflecting surfaces were employed. The latter bands are plotted to a larger scale in C'_1 and C'_2. The maxima in the spectrum to the left (not

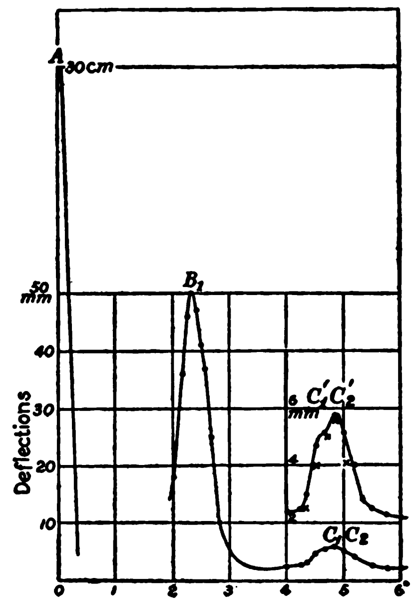


FIG. 20. — Muscovite mica.

plotted) were identical with the above. The wave-lengths of the maxima at C_1, C_2 are 18.4 and 21.25 μ (Rubens and Nichols) and are used in the calibration curve of grating No. 2, curve b, fig. 19.

RESIDUAL RAYS FROM CARBONATES.

CALCITE ($CaCO_3$).

(Grating No. 2. K = 0.2120 mm. Fig. 21.)

The plane cleavage faces of 3 large crystals were used in this examination. The spectrometer slits were 4 mm. wide. In fig. 21 the central

[1] It is a pleasure to note the general adoption of the expression " residual rays " for the meaningless " reststrahlen," formerly used. The English vocabulary seems sufficiently complete to enable writers to find equivalents to " étalon," " entladungsstrahlen," etc.

image A is plotted to one-fifth the scale of B_1 and B_2, while the scale of C'_1, C'_2 and D'_1, D'_2 is five times that of B_1, B_2. The sharp maxima at B_1 B_2 are due to the complex reflection band at 6.7 μ, previously studied. In the present case the maximum occurs at 1°49′, which corresponds to 6.78 μ. The wave-length of the maximum at 5° 45′, D_1, D_2 is 29.4 μ as determined by Aschkinass (*loc. cit.*). He located the maximum at C_1, C_2 at 11.4 μ in the rock-salt spectrum, but did not find it in the grating spectrum. From his observations he predicted a weak band in the region of 15 to 20 μ. The asymmetrical part of the reflection curve at +4° indicates a possible band at 14 to 16 μ, beginning also in the transmission curve

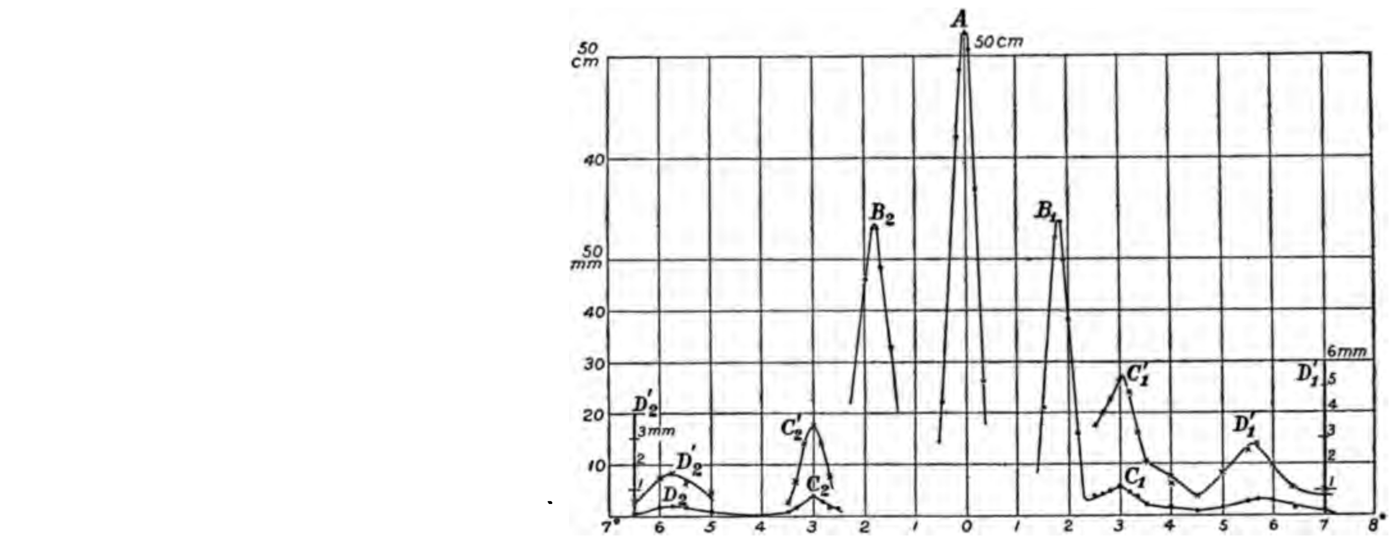


Fig. 21. — Calcite.

of calcite, previously studied (see Carnegie Publication No. 65, p. 70), where the substance becomes entirely opaque at 14 μ.

The band at 11.4 μ deserves further study because of the possibility of its being dependent upon the direction of polarization of the incident energy.[1] In the transmission curve of calcite previously studied (see Carnegie Publication No. 65, p. 70) it was found that the region of 9 to 14 μ is quite transparent. A small absorption band was found at 11.3 μ, which is so inconspicuous that it would appear impossible for it to give rise to selective reflection. Of all the substances examined this is the first example (see, however, nitrosodimethyl aniline) where a *small* absorption band apparently coincides with, or gives rise to, a reflecting band. In all other

[1] While this paper is in press, Nyswander (Phys. Rev., **26**, p. 539, 1908), using polarized light, found that the band at 11.3 μ is due to the complete absorption (reflection) of the extraordinary ray, the ordinary ray showing no trace of an absorption band in this region. At 14.1 μ is a band due almost entirely to the complete absorption of the ordinary ray.

cases the transmission curves show complete opacity in the region of a selective reflection band even for the thinnest film yet examined, viz, glass (see Carnegie Publication No. 65, p. 65). That the band at 29.4 μ is not influenced by the structure of the crystal is proven by the fact that Aschkinass found this band in white marble.

MAGNESITE ($MgCO_3$).

(Grating No. 2, fig. 22.)

In this examination three reflecting surfaces of the massive material were used, one of which did not have a high polish. The maxima at B_1, C_1, D_1 correspond to wave-lengths 6.7, 11.3, and 30.7 μ (5° 52′), respectively. In fig. 22 the maxima C'_1, C'_2 ($=11.3\ \mu$) and D'_1, D'_2 ($=30.7\ \mu$) are drawn to ten times the scale of B_1, B_2. The band at D_1 is

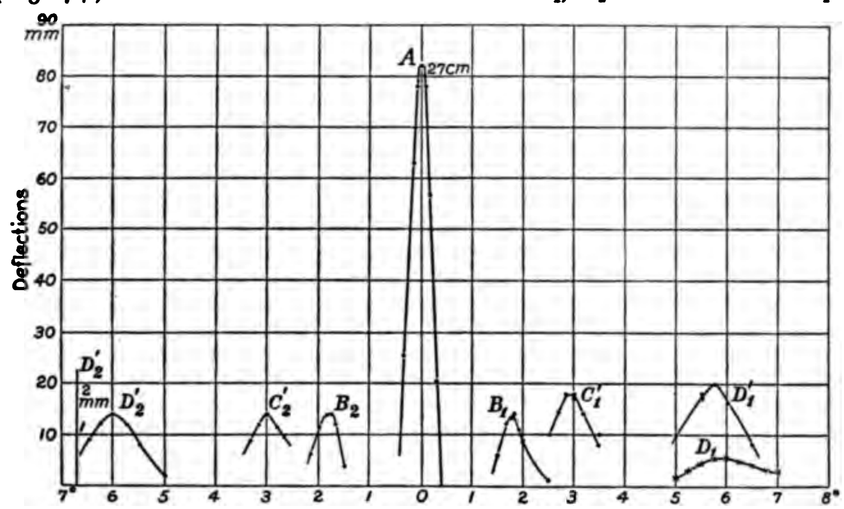


FIG. 22.—Magnesite.

plotted to the same scale as B_1 but only two reflecting surfaces were used. The magnesite maxima are identical with those of calcite (except at a possible greater wave-length, at 30 μ). This would seem to indicate that coincidence of the reflection spectra of chemically related groups of substances is a property which obtains throughout the spectrum. This is to be expected, but it seemed of interest to add further experimental evidence to support this view, by extending the observations into the remote infra-red. The bands at 29.4 μ are too weak to illustrate the effect of molecular weight, noticed at 6.7 to 7.2 μ in the carbonates.

RESIDUAL RAYS FROM CRYOLITE ($3NaF \cdot AlF_3$).

(Gratings No. 1; slits 4 mm.; fig. 23.)

Reasoning from the fact that cryolite is a fluoride of Na and Al, and from the behavior of fluorite (CaF_2), it was hoped to find this mineral to

have properties similar to fluorite. That the expectations were not fulfilled is perhaps to be attributed to the fact that the specimen was an hydrated alteration product, as will be noticed from its transmission spectrum (fig. 26), which shows that the mineral contained water.

In fig. 23 is given the reflection curve of cryolite, four large, well-polished surfaces being used. The central image was quite strong. The first-order

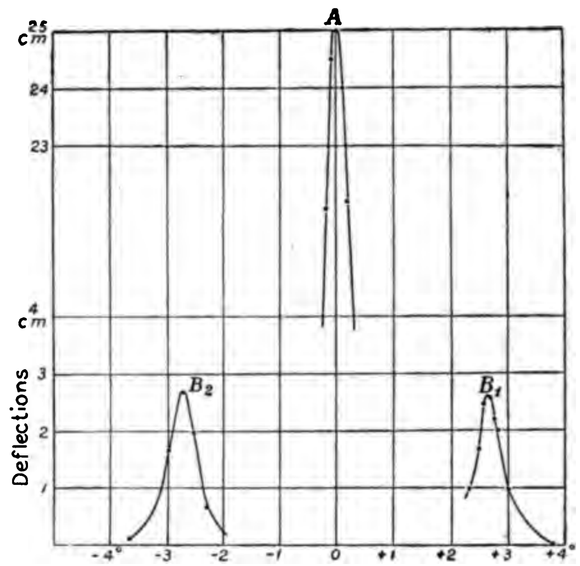


FIG. 23. — Cryolite.

diffraction band to the right and to the left is quite strong, being measured in centimeters instead of millimeters. This, of course, is partly due to the coarser grating. The mean angular position of the maximum is 2° 43′. From the calibration curve the wave-length of this maximum is 15.1 μ, which is just half the value of the most intense band of fluorite.

RESIDUAL RAYS FROM OTHER MINERALS.

DIASPORE [AlO(OH)].

In examining the following minerals grating No. 1 was used in order to obtain an intense spectrum. The slits were 4 mm., which is a little smaller than those used by others. In Carnegie Publication No. 65 the reflection spectrum of an intense double band was found at 14 to 15 μ. From its general trend it was hoped to find the reflection spectrum to contain further bands. Only two reflecting surfaces were available. With these, the maxima at 15 μ in the rock-salt spectrum were verified, but no bands were detected beyond this point.

STIBNITE (Sb_2S_3).

Stibnite was previously found to have a high reflecting power up to 15 μ, where it seemed to decrease. In the present examination, using three reflecting surfaces, this high reflecting power was found to continue throughout the infra-red. A small maximum was found at 2 μ, which no doubt belonged to the third-order diffraction band. When using aluminum mirrors a similar band was found at this point.

SPODUMENE [$LiAl(SiO_3)_2$].

Three large reflecting surfaces were used. The galvanometer was perfectly steady, so that 0.2 mm. deflections could have been read, but no radiation was detected beyond that due to the reflection bands at 9 to 10 μ previously examined with the rock-salt prism.

CELESTITE ($SrSO_4$). SELENITE ($CaSO_4 + 2H_2O$).

Three large cleavage specimens of each of these were examined, using slits 4 mm. wide. In the case of celestite the central image gave a deflection of 50+cm., but nowhere could radiation be detected except in the region of 9 to 10 μ previously studied. Aschkinass (*loc. cit.*) has predicted a band in the region of 50 μ for the sulphates.

APATITE [$Ca_5F(PO_4)_3$].

Three large ground and polished surfaces were used in this examination. No reflection bands were observed except at 9 μ, where an examination with a rock-salt prism showed a weak (20 per cent) double band. Apparently the phosphates have no strong reflection bands throughout the infra-red spectrum. This is just the opposite of what has been described in Chapter II on the oxides, where very intense bands were frequently observed.

CYANINE ($C_{29}H_{35}N_2I$).

(Grating No. 2; slits 4 mm.)

This substance was melted between glass plates, which were then split apart, thus leaving plane smooth surfaces. Three such films on glass were examined. It was previously found (see Carnegie Publication No. 35, p. 82) that cyanine is very opaque at 6 to 8 μ. The central image gave a deflection of 50+cm., and there was still a little reflected energy to be detected at 25 μ, indicating a high reflecting power, but no reflection bands could be detected throughout the spectrum.

SILICATES.

The reflection curve of mica has already been described in connection with the calibration of the instrument. This examination included also serpentine, albite, and microcline. The grating spectrum showed the reflection bands at 9 μ, but beyond this no appreciable radiation could be detected. This, of course, was to be expected for serpentine, for which

the rock-salt prism showed only weak maxima at 8 to 10 μ. In a previous study of quartz with a rock-salt prism a narrow, quite intense band was located at 12.5 μ, which had not been recorded by Rubens and Nichols. In the present examination, using grating No. 1, the maximum was found at 2° 21′ (=12.8 μ), while with grating No. 2 the maximum was located at 3° 20′ (=12.5 μ). In table I are given the maxima of the reflection bands of the minerals studied.

TABLE I. — MAXIMA OF REFLECTION BANDS.

	μ	μ	μ	μ	μ	μ	μ
Smithsonite, $ZnCO_3$	6.65	7.05					
Cerussite, $PbCO_3$	6.9	7.25					
Strontianite, $SrCO_3$	6.68						
Witherite, $BaCO_3$	6.70	6.98					
Malachite, $CuO \cdot CO_2 \cdot H_2O$	6.66	7.3	7.8?				
Azurite, $3\,CuO \cdot 2\,CO_2 \cdot H_2O$	6.65	7.32	7.8				
Dolomite, $CaMg\,(CO_3)_2$	6.58	6.95					
Siderite, $FeCO_3$	6.6	7.1					
Calcite, $CaCO_3$	6.4?	6.5	6.62	6.85 to 7.0	11.4	16.?	29.4
Aragonite, $CaCO_3$	6.53	6.75	7.0?				
Magnesite, $MgCO_3$	6.42	6.65	6.9	11.4	30.2		
Scheelite, $CaWO_4$	11.3 to 12.5	11.3 11.8 12.4					
Zircon, $ZrSiO_4$	10.1	10.6	11.0	11.6			
Wulfenite, $PbMoO_4$	3.2	6.5	11.75	13.1			
Rutile, TiO_2	13.6						
Cyanite, $Al_2O_3 \cdot SiO_2$	9.3	9.78	10.28				
Corundum, Al_2O_3	11.0	11.8	13.5				
Topaz $(Al \cdot F)_2SiO_4$:							
Yellow	10.05	10.6	10.9	11.3			
White	9.9	10.45	11.0	12.?			
Spodumene, $LiAl(SiO_3)_2$	9.18	9.7	10.4				
Muscovite Mica, $H_2KAl_3(SiO_4)_3$	9.2	9.7	10.2	18.4	21.25		
Cryolite, $3\,NaF \cdot AlF_3$	3.0	4.7	6.0	15.1			
Beryl, $Be_3Al_2(SiO_3)_6$	8.15	9.2	9.9	10.4			
Quartz:							
Glass	7.8	8.4	8.8				
Crystalline	8.4	9.02					

CHAPTER V.

ON REGULAR AND DIFFUSE REFLECTION.

From his previous work on the reflecting power of silicates the writer concluded that a surface like the earth or the moon, which is composed of silicates, must be selectively reflecting. From an examination of some of the subsequent discussions of the reflecting power of the moon, it would appear that a matte surface can not be selectively reflecting. In fact, the whole misunderstanding seems to hinge on this point. Since the surfaces of the minerals examined by the writer were, in nearly all cases, plane and highly polished, there was no "diffuse reflection," which is an entirely different question from the one of low, "practically zero," reflection, which the writer found to be a common property of certain minerals, for certain regions of the infra-red spectrum.

When energy is reflected from a plane smooth surface, it is commonly called "regular" (or, less accurately, "specular") reflection. On the other hand, energy reflected from a rough surface suffers "diffuse" reflection. The rough surface is equivalent to numerous small, plane, reflecting surfaces, the planes of which lie in all directions. In "diffuse reflection" for each infinitesimal surface, the ordinary laws of reflection are obeyed in full, unless the linear dimensions of the reflecting surface or of the rugosities or inequalities on it are small compared with the wave-length. However, the unpolished surface as a whole destroys all phase relation between the particles in the reflected wave-front, which is no longer plane, but irregular. (See Wood's Optics, p. 36.) This irregularity decreases as the angle of incidence increases, so that for a given roughness we get regular reflection. The long waves will be reflected first, then the shorter ones. "Smoked glass, which at perpendicular incidence will show no image of a lamp at all, will at nearly grazing incidence give an image of surprising distinctness, which is at first reddish, becoming white as the angle increases." (Wood's Optics, p. 37.)

The amount of energy reflected "regularly" from a plane surface will depend upon the reflecting power of the substance. Now, the reflecting power R of any substance is related to its index of refraction n and its absorption coefficient k by the equation

$$R=\frac{(n-1)^2+k^2}{(n+1)^2+k^2}$$

For "transparent media," *i. e.*, "electrical non-conductors" (see

Drude's, also Schuster's Optics), the absorption coefficient is so low that it is negligible, and the reflecting power is a function of only the refractive index. Here the reflecting power is low, only 4 to 6 per cent, and decreases with increase in wave-length. All transparent media thus far examined (except silver chloride) have bands of selective reflection. In these bands the absorption coefficient k attains high values.

If k becomes sufficiently large (see Schuster's Optics, Pockel's Crystallographie, 1906), of the order unity, the absorption affects the reflecting power, and the heat and light waves no longer enter the substance, but are almost totally reflected, as in metals, whence the name, "bands of metallic reflection." For metals, "electrical conductors," the absorption coefficient

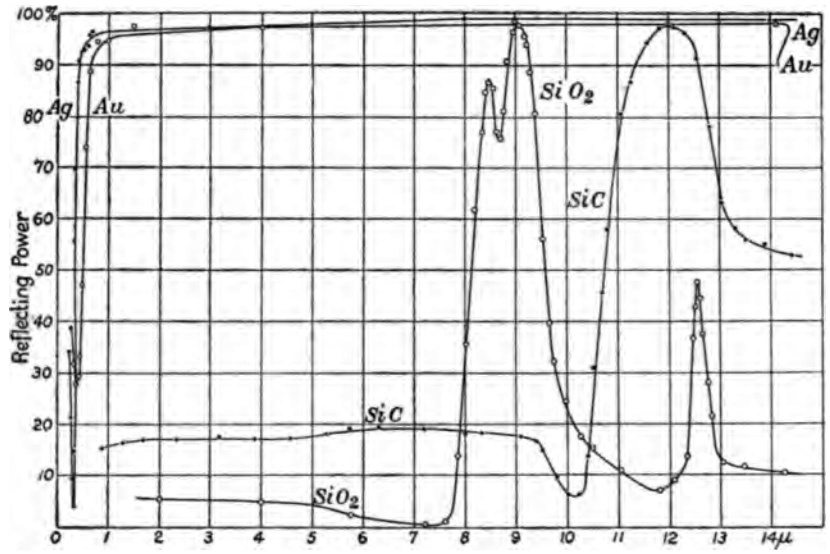


FIG. 24. — Reflecting power; gold, silver, quartz, carborundum.

is so large that nearly all the energy for all (gold and silver are exceptions) wave-lengths is reflected. In other words, the reflecting power of plane surfaces ("regular reflection") of "transparent media" (electrical non-conductors) will be low in all regions of the spectrum, except where there are bands of "metallic reflection." It is evident that the diffuse reflection from rough surfaces of transparent media must also be selectively reflecting. For electrical conductors the reflecting power is high throughout the infra-red spectrum. The great dissimilarity in the reflecting power of these two classes of substances is well illustrated in fig. 24, which contains the graphs of the reflecting power of gold, silver, quartz, and carborundum.

Apropos of the illustration just quoted, of the reflection from smoked glass, Very[1] "records that the percentage of reflected rays, as measured by

[1] Very: Astrophys. Jour., 8, p. 278, 1898.

the bolometer, is especially large (perhaps two or three times the usual proportion) in the narrow crescent moon where the rays suffer a grazing reflection at a large angle of incidence, the emission under the corresponding angle of emission being small." This is particularly noticeable in the early forenoon. Very's[1] recent discussion gives the impression that, in the moon, "specular reflection" is something to be sought for at the angle of reflection with the sun, at which the image of the sun in rays of 8.5 to 10 μ may be isolated by using a screen with a pinhole aperture. Here "specular reflection" appears to be used in the sense of "regular reflection." The writer is not discussing this limiting case, but it appears self-evident that a matte surface like a plane surface can be selectively reflecting, and hence that a surface of quartz, for example, which, if smooth, reflects like a metal for wave-lengths 8.5 and 9.03 μ and like a transparent medium for all other wave-lengths, must still reflect selectively when it is rough.[2] Hence, in the stream of energy reflected in any direction the density will be greatest for wave-lengths 8.5 to 9.03 μ. Of course these bands of "metallic reflection" will now be less intense. Since the energy density in every direction must be greatest for wave-lengths 8.5 to 10 μ, one would expect to detect this difference in any direction, and not simply at the angle of regular reflection.

If, then, the eye were sensitive to the infra-red quartz would have a "surface color" corresponding to wave-lengths 8.5 and 9.03 μ. In speaking of surface color, however, a sharp distinction must be made, for the reflecting power of these bands is as great as that of metals, although the substance is a non-conductor; whence one would expect the reflecting power to be low. In the case of transparent non-conductors the surface color is due less to reflection than to absorption, for it is due to absorption that the reflected light is deprived of some of its constituents and becomes colored. However, on the long wave-length side of the absorption band the reflecting power is high, which contributes to the color. For example, the aniline dyes, such as fuchsine, have a low reflecting power (as compared with metals) and yet they possess surface color. Pigments belong to the class of substances having "body color." On the other hand, metals, such as gold and copper, also have a surface color, due to selective absorption. They are electrical conductors, however, and theoretically would totally reflect all radiations for all wave-lengths. This has been established

---

[1] Very: Astrophys. Jour., 24, p. 351, 1906. Here the writer is quoted as having found "that common minerals reflecting diffusively" from 4 to 8 μ have bands of metallic reflection from 8 to 10 μ.

This quotation is erroneous. The writer found that the reflection was "regular" for all wave-lengths, but that from 4 to 8 μ the reflecting power is low, as in cases of transparent media having low refractive indices, while from 8 to 10 μ the reflecting power is high, like metals, hence called "metallic reflection."

[2] See footnote, p. 146, for experimental evidence supporting these statements.

for long wave-lengths.[1] The reflection curves of such metals as gold and silver, however, are entirely different from those of the electrical non-conductors (see fig. 24). In the former the extinction coefficient is always high, while in the latter the extinction coefficient fluctuates through a great range. In quartz the ions have a proper period of undamped electrical vibration which almost totally reflects the wave trains in the region of 8.5 and 9.03 μ, while for the shorter wave-lengths the vibration periods are more damped, the reflection is enormously decreased, and more of the energy is absorbed. In the case of a reflecting surface composed of electrically non-conducting material, of the total energy falling on the surface, the reflected energy in and near the visible spectrum will consist of that reflected from the surface and that part which enters the particles and is returned, due to internal reflection. In the region of 8 to 10 μ (for silicates) almost all the observed energy will be reflected from the surface, and hence none will be reëmitted due to internal reflection. As a whole, then, what the writer found is that the silicates reflect like "transparent media" for all wave-lengths up to 8 μ and like metals from 8.5 to 10 μ. In other words, it may be said that in quartz (SiO_2) the silicon ions retain the proper period of undamped electrical vibration which they would have in the metal, silicon, for wave-lengths 8.5 and 9.03 μ, while, for all other wave-lengths, the vibration periods are more damped and the reflecting power is decreased.

---

[1] Hagen and Rubens: Ann. der Physik, 8, p. 1, 1902.

PART VI.

INFRA-RED TRANSMISSION SPECTRA.

CHAPTER I.

INTRODUCTION.

With the accumulation of data the evidence becomes more and more convincing that there are no strong bands of selective absorption (except in the colored glasses given on a later page) in the region of short wave-lengths, near the visible spectrum, such as are to be found beyond 6 μ. Material suitable for investigation is obtained with difficulty. The present contributions to the subject of transmission spectra is rather meager in volume, but several of the substances show peculiarities worth recording.

The apparatus and methods of examining the following material, consisting of a rock-salt prism and mirror spectrometer, were described in Carnegie Publication No. 65. Instead of the radiometer, an improved Rubens[1] thermopile was used to measure the energy in the transmission spectra.

GROUP I: TRANSMISSION SPECTRA OF VARIOUS SOLIDS.

MOLYBDENITE (MoS).

(From Yorkes Peninsula, South Australia. Foliated, distorted; thickness, $t=0.05$ and 0.31 mm.; fig. 25.)

In the preceding work it was noticed that the sulphides are, in general, quite transparent. Sphalerite (ZnS) was found to have wide absorption

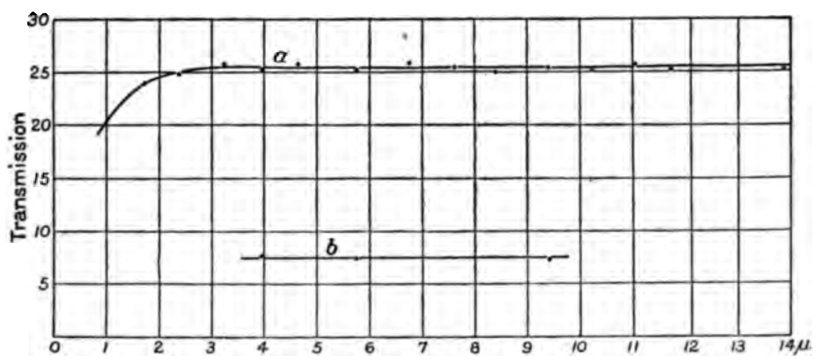


FIG. 25. — Molybdenite.

bands at 3 and 15 μ. On the other hand, stibnite (Sb_2S_3) is opaque to the visible and has a second absorption band beyond 15 μ. In the interven-

[1] See Appendix II.

ing part of the spectrum the absorption coefficient is very small, and the loss of energy is due to the high reflecting power, which is about 40 per cent.

Molybdenite differs from stibnite in that it is very opaque throughout the spectrum, examined to 15 μ. The two specimens examined were thin folia, only 0.05 and 0.31 mm. in thickness (curves *a* and *b*, fig. 25). From the greatly decreased transmission of the thicker piece, it will be noticed that the loss of energy is due to absorption rather than reflection. The absorption coefficient has not been computed, but an inspection of the curves shows that it must be large. By increasing the thickness six times the transmission is decreased 18 per cent, while in stibnite, by increasing the thickness five times, the transmission is reduced only about 5 per cent, in the region of general absorption.

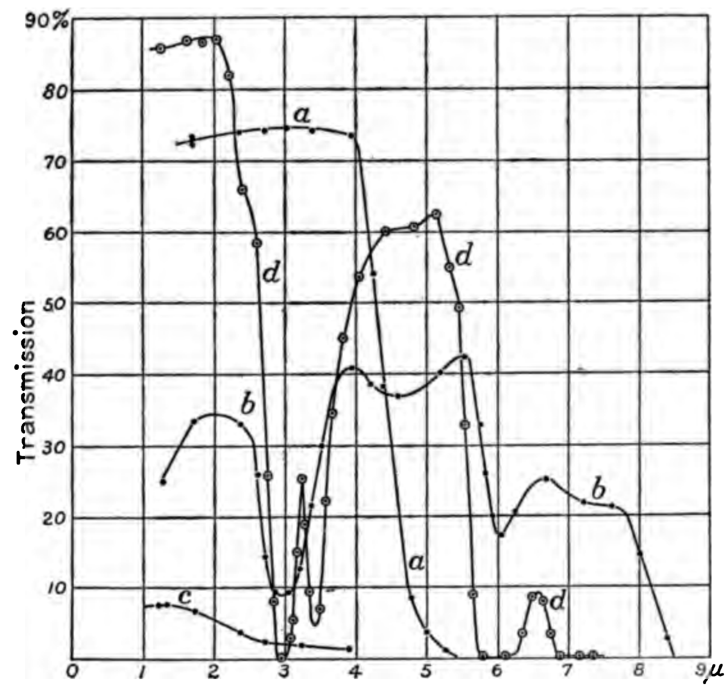


FIG. 26. — Kuntzite (*a*); Cryolite (*b*); Carborundum (*c*); Nitrocellulose.

KUNTZITE [$LiAl(SiO_3)_2$].

(From Pala, California. Cleavage piece, parallel to *m*; transparent; $t = 1.05$ mm. Curve *a*, fig. 26.)

This mineral, which is violet spodumene, is obtainable in large specimens, hence it was of interest to determine its transparency to infra-red radiation. It is lacking in the small band of SiO_2 at 2.95 μ and is more opaque than quartz in the region of 1 μ, so that it would not be more serviceable than the latter in optical work.

CARBORUNDUM (SiC).

(Artificial product; $t = 1.27$ mm. Curve *c*, fig. 26.)

The specimen examined was a flat crystal which transmitted blue light, and reflected yellowish-green light. It has remarkable optical properties,[1] especially a high value for the refractive index. It is opaque in the ultraviolet (Jewell) and beyond 2 μ in the infra-red. In this respect the transmission curve *c*, fig. 26, is very remarkable as compared with all the other substances examined, of which only one, viz, mellite, is as opaque to infrared rays. The reflection curve was examined previously; it also shows remarkable properties.

CRYOLITE ($3NaF \cdot AlF_3$).

(From Ivigtut, Greenland. Massive, semitranslucent; $t = 2.3$ mm. Curve *b*, fig. 26.)

From the composition of the material it was hoped to find this to be more transparent to heat rays than usually has been the case with minerals. Possibly a pure crystal of cryolite would be different. From the absorption bands (curve *b*, fig. 26) it will be noticed that this specimen contained water of crystallization.

Thomsenolite ($NaLiAlF_6 + H_2O$), previously examined, is an alteration product of cryolite, and from the similarity of the transmission curves it would appear that this sample of cryolite had already undergone some alteration into the hydrated mineral.

NITROCELLULOSE (TRANSPARENT "CELLULOID").

(Curve *d*, fig. 26; $t = 0.138$ mm.)

Transparent celluloid is a mixture of nitrocellulose [$C_{12}H_{16}(NO_2)_4O_{10}$] and camphor ($C_{10}H_{16}O$). The transmission curve which was obtained with a fluorite prism and bolometer is conspicuous for two regions of great absorption, with maxima at 3 μ, 3.43 μ, and 6 μ.

Camphor is a very complex carbohydrate. Its alcoholic properties, OH groups, should cause an absorption band at 3 μ (2.95 μ in Carnegie Publication No. 35, p. 58, for rock-salt prism). Its ketone properties, CO groups (perhaps aldehyde properties, CHO groups), should cause a strong band at 6 μ. Excellent examples of OH groups are (see Carnegie Publication No. 35, p. 108) carvacrol and thymol, of CHO groups are benzaldehyde, cuminol, eucalyptol, colophonium, and venice turpentine, and of both these groups is terpineol. The band at 3.43 μ is characteristic of the CH_2-groups.

Excepting in intensity, the transmission curve is similar to that of collodium (Carnegie Publication No. 65, p. 60), which is also a complex compound of cellulose. It seems rather remarkable that the characteristic vibration period of these groups of atoms is not affected by the complexity of the compound.

---

[1] Jewell: Physical Review, 24, p. 239, 1907.

SIDERITE ($FeCO_3$).

(From Allevard, France. Cleavage piece; $t = 1.2$ mm.; grayish color; translucent to transparent. Fig. 27.)

This specimen was examined in connection with the carbonates previously studied. The complex band, with maxima at 3.4, 3.9, and 4.6 μ, is in common with the other carbonates. In a very thin section of calcite

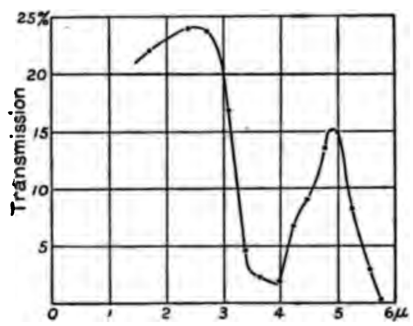


FIG. 27. — Siderite.

($CaCO_3$) this region was resolved into sharp bands, having maxima at 3.44, 3.93, and 4.6 μ. This sample furnishes additional proof that the large groups of chemically homologous compounds have similar absorption spectra.

WULFENITE ($PbMoO_4$).

(From Red Cloud Mine, Yuma County, Arizona. Deep-yellow color; $t = 2.1$ mm. Curve *a*, fig. 28.)

This mineral is of interest in connection with a study of the oxides, *e. g.*, TiO_2, SiO_2, etc. The transmission curve *a*, fig. 24, shows wide

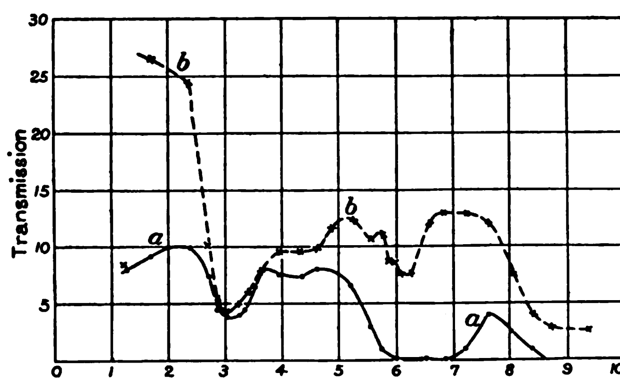


FIG. 28. — Wulfenite (*a*); Phosphorus.

absorption bands at 3.15 and 6.5 μ, and complete opacity beyond 9 μ, where there is a band of metallic reflection.

Phosphorus (P).

(Solid film melted between plates of fluorite. $t=0.8$ mm. (?). Curve *b*, fig. 28.)

Phosphorus was examined in order to answer an inquiry whether it could be used for prisms contained in vessels with quartz or fluorite windows. The yellow stick phosphorus was used. It was melted under water (at 44° C.), poured on a glass plate, and pressed into a thin sheet by means of a second plate of glass. This thin sheet was then placed between two plates of fluorite and the edges covered with soft wax. As will be noticed in curve *b*, fig. 28, the transmission curve shows bands due to water which adhered to the phosphorus. The latter melted during the latter part of the examination. The transmission curve includes the fluorite plates, which were not clear, and hence increase the observed absorption.

Quartz (SiO_2).

($t=3$ mm. Curve *b*, fig. 29.)

The sample examined was used as a window on the spark-tube in the emission spectra of metals in hydrogen, Part VII. The curve shows that emission lines, if of appreciable intensity, would be transmitted out to 4 μ.

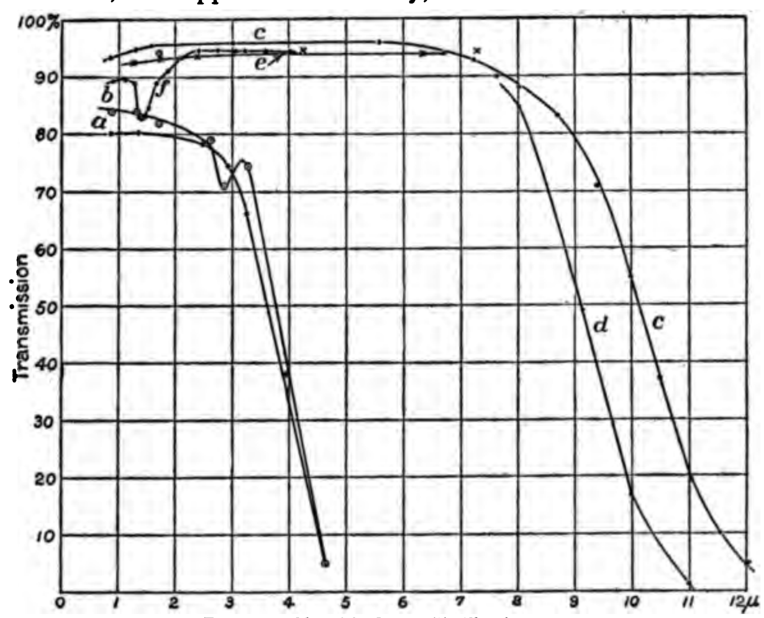


Fig. 29. — Glass (*a*); Quartz (*b*); Fluorite.

Glass.

(Thickness = 0.75 mm. Curve *a*, fig. 29.)

This sample was examined in connection with prospective work on radiation from incandescent lamps. The transmission is uniform (80 per cent) out to 2 to 2.4 μ. From this it will be seen that the maximum of the energy spectrum of the filament will not be affected by the glass bulb.

Fluorite (CaF).

(Curve *c*, $t=2.28$ mm.; curve *d*, $t=10$ mm.; curve *e*, $t=1.84$ mm.; curve *f*, $t=3.85$ mm. light-green color; fig. 29.)

On account of the increased scarcity of this material, it is of interest to determine the effect of inclusions upon the transmission. In fig. 29, curve *c* was a perfectly clear specimen; while curve *e* contained numerous small inclusions, or, perhaps more exactly, small cleavage planes. The latter when held at a distance of 30 to 50 cm. from the eye appeared quite blurred. Nevertheless, throughout the infra-red the loss of energy is only about 2 per cent greater than that of clear fluorite. This is to be expected; for each cleavage plane reflects some of the light, and the magnitude of this reflection, since it depends upon the refractive index, decreases with increase in wave-length. Curve *f* shows the transmission of a specimen of light yellowish-green fluorite (see Carnegie Publication, No. 65, p. 69, for another example) which has an absorption band at $1.4\,\mu$, hence not suitable for a prism. This specimen was free from inclusions.

Carbon (C).

(Curves *a*, *b*, *c*, lampblack; curve *d*, diamond; fig. 30.)

The commonest and most conspicuous example of the effect of structure upon absorption is to be found in carbon in the form of lampblack and

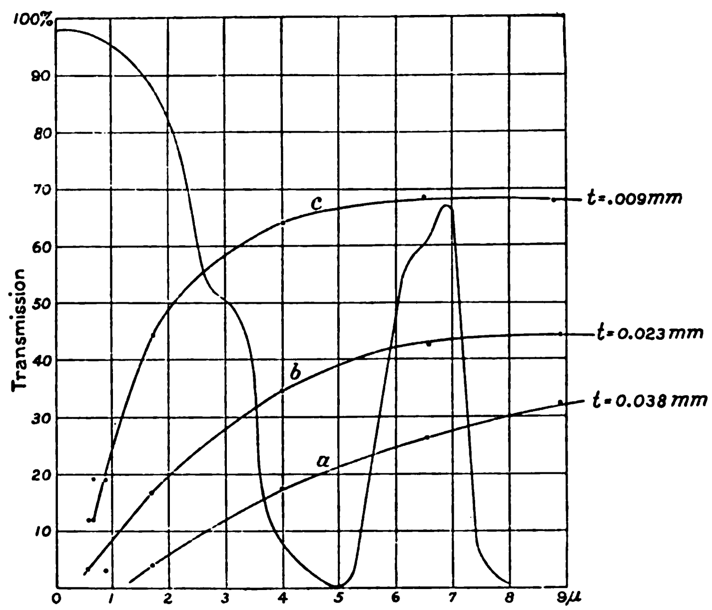


Fig. 30. — Carbon (*a*), (*b*), (*c*); Diamond.

of diamond. Since the observations on these two substances are published in separate and rather isolated places they are incorporated here for completeness of illustration of the effect of structure. The transmission curves

a, *b*, *c*, thickness 0.038, 0.023, and 0.009 mm., respectively, of lampblack are due to Ångström.[1] The transmission curve of diamond is due to Julius.[2] The lampblack is opaque to the visible and shows an increase in transmission with wave-length. The diamond crystal is transparent to the visible and has well-defined absorption bands at 3, 4, and 5 μ and complete opacity beyond 8 μ. A band of metallic reflection is predicted at 12 μ, which happens to coincide with the band of carborundum.

It seems rather remarkable that diamond should have one of its principal absorption bands in the region where carbohydrates have a wide band of great transparency.

GROUP II: TRANSMISSION SPECTRA OF VARIOUS SOLUTIONS.

The data presented here were obtained several years ago (but not published) in connection with an investigation of methods of measuring radiant efficiencies.[3] One of the methods of measuring the efficiency of an illuminant, *i. e.*, the ratio of the light emitted to the total radiation, is to absorb the infra-red by means of a water cell. The idea persists even to this day that a water solution of potassium alum absorbs more heat than does clear water, although Donath and others demonstrated, long ago, that this is not the case; the data herewith presented is further proof of this fallacy. During the present year (Phys. Zeitschrift, 1907) measurements of radiant efficiencies have been made using a water solution of ammonium-iron alum, and it was claimed that the solution was more opaque than pure water. A transmission curve of this substance will be shown presently which indicates a greater opacity than water. The iron alum oxidizes readily and it is difficult to keep the solution clear.

The problem was recently presented to the writer by the Astrophysical Observatory to suggest a substance (see asphaltum) that absorbs all the visible or all the infra-red energy, the dividing line being 0.76 μ. Such a substance would of course be an ideal energy filter; but no such substance is known. Indeed, from all the substances examined, it appears that none (at least none of the common ones) have large absorption bands near the visible. Beryl[4] is recorded as having a large band at 0.89 μ, when examined in polarized light. Cyanine would be a fairly good material for absorbing the visible, but it is very opaque in the region of 6 to 8 μ. Iodine would be much better material for absorbing the visible, and transmitting the infra-red. Its absorption band, at about 7.3 μ, is very weak. The absorption band of iodine in the visible spectrum corresponds closely with the sensibility curve of the eye. Since we are concerned only with the light that affects the eye, the fairest rating of efficiencies would be to com-

[1] Ångström: Wied. Annalen, **36**, p. 717, 1889.
[2] Julius: Königkl. Akad. Wiss. Amsterdam, Deel I, No. 1, 1892.
[3] Nichols & Coblentz: Phys. Rev., **17**, p. 267, 1903.
[4] Königsberger: Ann. der Phys. (3), **61**, p. 687, 1897.

pare the energy that affects the normal eye to the total energy. This would lower the present efficiencies of sources that are rich in the red, which color affects the eye but little.

The use of iodine in solution is prohibited by the selective absorption of heat rays by all known solvents. On the other hand, solid iodine evaporates readily, so that it would be impossible to keep a solid film of uniform thickness for any great length of time.

Asphaltum.

(Curve *c*, $t=0.1$ mm.; $a=0.0005$ mm.; $b=0.03$ mm.; $d=0.005$ mm.; fig. 31. For the complete curve, to 14 μ, see Carnegie Publication No. 35, p. 75, and fig. 44, p. 198.)

The next best substance to iodine for absorbing the visible and transmitting the infra-red is asphaltum, which is a solid hydrocarbon, previously examined. This substance can be formed into films of any desired thickness. In fig. 31 curves *a* and *b* are due to Nichols.[1] From the curves it

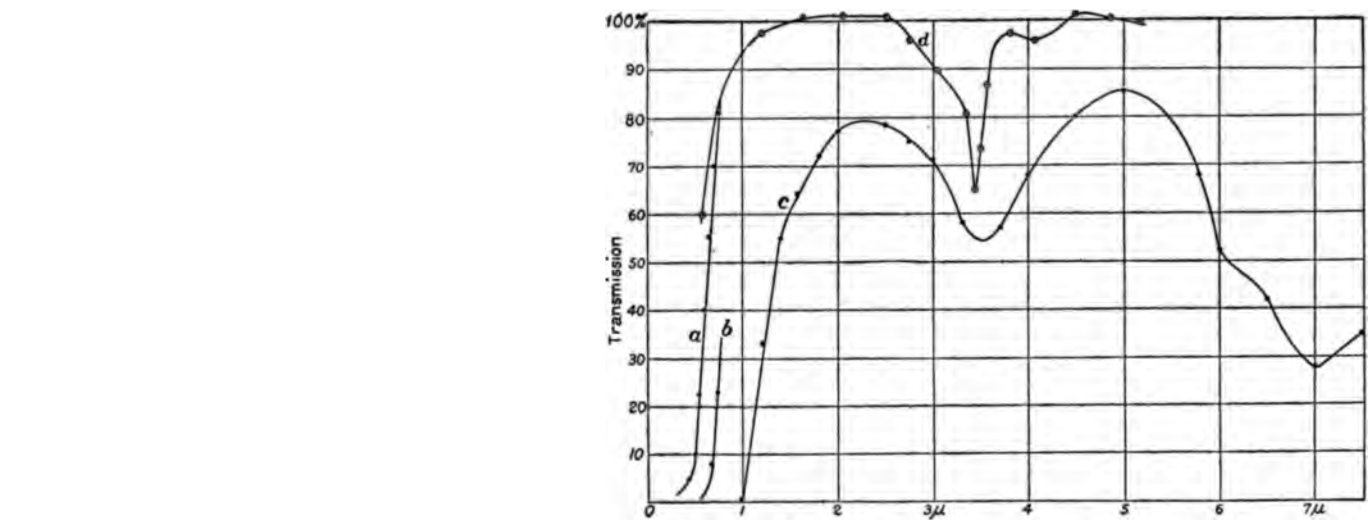


Fig. 31. — Asphaltum.

will be seen that a thickness can be selected which fulfills the conditions of complete transparency beyond 0.7 μ better than any other common substance. Even the thick film (curve *c*, $t=0.1$ mm.), which transmitted a trace of red, shows great transparency, after passing beyond the effect of the absorption band in the visible. A film absorbing up to 0.65 or 0.7 μ would be practically transparent in the infra-red (see Carnegie Publication No. 35, p. 17), where, for a very thin film of water, the small absorption band at 4.75 μ, similar in intensity to those of asphaltum, has entirely disappeared. By using a clear rock-salt plate, covered on both sides to prevent the action of moisture, a fair standard could be produced. The

[1] E. L. Nichols: Phys. Rev., 14, 204, 1902.

asphaltum may be applied to the rock-salt as a thin varnish, the volatile parts of which evaporate in a short time.

Asphaltum varnish, applied in an extremely thin coating, forms an excellent protecting surface for radiometer or radiomicrometer windows made of rock-salt. It might also be used advantageously as a covering for rock-salt prisms to protect them from moisture. The pair of films of asphaltum to be used for such purposes can be made extremely thin, and are almost transparent, as shown in fig. 31, curve *d*, which was of a light amber color showing but little absorption in the visible spectrum. The film was prepared from commercial asphaltum varnish, which is a very thick solution, by diluting it with gasoline. This precipitates the very insoluble constituents, which apparently are simply held in suspension, and by experimenting on the amount of gasoline to be added, a film or pair of films of any desired thickness may be produced by a single dipping of the plate or prism. Of course, a thicker film may be formed by using a thicker solution, or by applying several coats of the thin solution. By filtering the dilute solution through cotton wool or through filter paper the black insoluble asphaltum particles are removed. The dried film is then homogeneous and perfectly free from even traces of black particles. The gasoline must be quite free from moisture, otherwise there is likely to be a slight action on the rock-salt surfaces, and the dried film will not be so homogeneous as that obtainable on a glass plate. It may be possible to apply a homogeneous film of paraffin or of ozokerite, which is white, and which, on account of its low refractive index, will reflect less than a rock-salt surface; but neither of these substances are as satisfactory as asphaltum purified, as indicated above. Such surface coverings for hydroscopic substances are, of course, useful only where the radiometer and prism are used in making relative comparisons, *i. e.*, it is not adapted to making spectral energy measurements of sources of radiation, where the absorption of the apparatus and the atmosphere must be eliminated.[1] Curve *d* is for two films on a plate of glass, 0.175 mm. thick. The values are obtained by dividing the observed transmission, when the glass was coated with asphaltum, by the observed transmission through the clear glass. The fact that the transmission is greater than 100 per cent is due to the higher reflecting power of glass, for which no correction was made.

---

[1] Since writing this, Dr. A. Trowbridge, at the Washington Meeting of the American Physical Society, April, 1908, described the transmission of extremely thin films of collodium (Carnegie Publication No. 65, p. 60, fig. 46) and their application to rock-salt as a protecting surface. For the region of the spectrum up to 6 μ there are no prominent absorption bands, and the small ones at 3.3 μ have almost entirely disappeared in the thinnest films, which are of the order of a light-wave in thickness. Collodium is said to be slightly hydroscopic, but whether it is sufficiently so to become separated from the rock-salt is unknown. At this meeting it was learned that at the Astrophysical Observatory it is proposed to use asphaltum varnish to protect the large rock-salt prism which is about 18 cm. high.

Alum Solution.

(Saturated solutions at 0° C.; cell 1 cm. thick; fig. 32.)

In fig. 32 are given the transmission spectra of water (o–o–o–o) and of solutions of the alums of potassium (x–x–x), ammonium (•-•-•-•), and of ammonium-iron. The curves are due to E. F. Nichols[1] and are included here because of their bearing upon the present data. The transmission curves of the solutions of potassium and of ammonium alum are identical with that of water. The ammonium-iron alum [$(NH_4)_2Fe_2(SO_4)_7$]

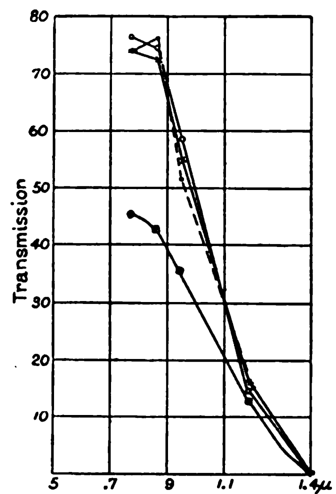


Fig. 32.—Water o–o–o; Potassium alum x–x–x; ammonium alum •–•–•–•; ammonium iron alum (lowest curve).

shows greater opacity, which from the trend of the curve appears to extend into the visible spectrum, due perhaps to a trace of iron oxide which is avoided with difficulty. The transmission curve of a clear plate of alum 4 mm. in thickness is shown in curve *a*, fig. 33.

Borax and Potassium Permanganate.

(Cell 1 cm. thick; glass walls; fig. 33.)

In fig. 33 are given the transmission curves *b* of borax ($Na_2Br_4O_7$) and curve *d* of potassium permanganate ($KMnO_4$). The latter solution was not saturated. The results show that there is no increased absorption of the solution over that of pure water, except in permanganate, which, of course, is almost opaque to the visible.

Lanthanum Nitrate ($LaNO_3$); Didymium Nitrate [$Pr,Nd(NO_3)_3$]; Sulphuric Acid (H_2SO_4); Liquid Glass (Na_2SiO_3).

(Cell 1 cm. Concentration of nitrates unknown. Fig. 34.)

In fig. 34 are given the transmission curves, *a* of sulphuric acid, *b* of lanthanum nitrate (solution), *c* of didymium nitrate (solution), and *d* of

[1] E. F. Nichols: Phys. Rev., 1, p. 1, 1896.

liquid glass. The sulphuric acid is more transparent than water, while the didymium nitrate has a sharp absorption band at 0.76 μ. The latter

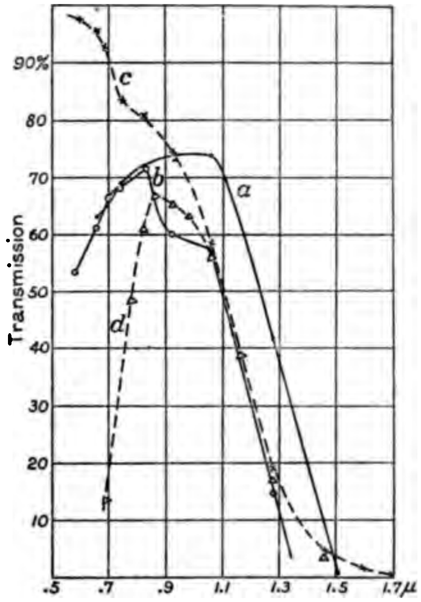


Fig. 33. — Potassium alum (*a*); Borax solution (*b*); Water (*c*); Potassium permanganate solution.

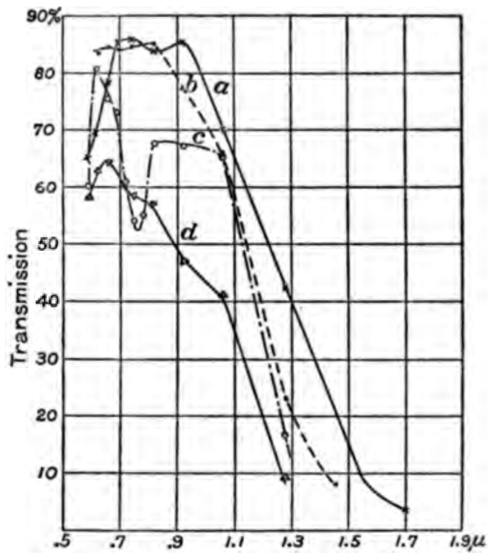


Fig. 34. — Sulphuric acid (*a*); Lanthanum nitrate (*b*); Didymium nitrate (*c*); Liquid glass.

have absorption bands in the visible, so that they would not be useful for efficiency work. The same is true of liquid glass.

Chlorides of the Yttrium Group (Sc, Yt, La, Yb); Neodymium Nitrate [$Nd(NO_3)_3$].
(Cell 1 cm. Concentration unknown. Fig. 35.)

These solutions, like the preceding ones, were obtained from the Chemical Laboratory of Cornell University, and the concentration was unknown. They were examined to learn whether the sharp absorption bands in the visible are also to be found in the infra-red. It will be noticed that the didymium nitrate (curve *b*, fig. 35) has two bands at 0.78 and 0.98 μ, while the yttrium group of chlorides have a band in common with didymium at 0.98 μ.

GROUP III: TRANSMISSION SPECTRA OF COLLOIDAL METALS.

The metals and non-metals present two distinct types of absorption, of reflection and of emission spectra. The metals (electrical conductors), even in very thin films, are extremely opaque to all radiations throughout the spectrum, except gold, silver, and copper, which have narrow transparent bands at 0.32, 0.5, and 0.6 μ, respectively.[1] The opacity is really due to

[1] Hagen & Rubens: Ann. der Phys., 8, p. 432, 1902; Javal: Ann. de Chim. et Phys. (8), 4, p. 137, 1895.

their high reflecting power, which is uniform throughout the infra-red. Their emission (arc and spark) spectra consist of numerous fine lines, which occur throughout the visible and ultra-violet part of the spectrum.

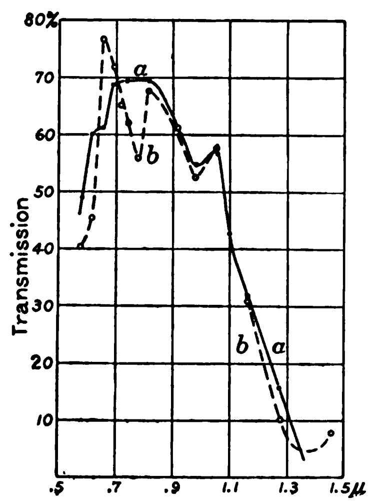


FIG. 35. — Chlorides of Yttrium Group (a); Neodymium nitrate.

No strong lines have yet been found in the infra-red, except in the alkali metals. On the other hand, the non-metals (insulators) have absorption bands throughout the spectrum. Their reflecting power is low, and in some compounds is highly selective in the infra-red. They have emission lines which extend far into the infra-red. The elements on the border line between metals and non-metals are of peculiar interest, and the reflecting power of their compounds deserves further study. A notable example is silicon, which from the known properties of non-metals would be expected to have a uniformly low reflecting power throughout the infra-red; in the form of a compound, SiO_2, the reflecting power at 8.5 and 9 μ attains a value as high as that of metals. The elements iodine, selenium, and sulphur have a uniformly low reflecting power. It would be interesting to learn whether only the compounds of non-metals have bands of selective reflection in the infra-red; all of our present data indicate that only in a compound (*cf.* SiO_2) do the ions of non-metals attain a freedom such as obtains in metals.

SILVER.

(Colloidal film, on glass. Curve *b*, fig. 36.)

The film examined was made[1] by Prof. R. W. Wood, and was of a deep ruby-red color. In fig. 36, curve *b*, is given the transmission curve of a thin uniform film of colloidal silver, deposited on glass. The transmission begins in the red, and increases uniformly throughout the infra-red to 4 μ, beyond which it was not possible to extend the observations on account of the opacity of the glass. This is exactly the reverse effect observed with a metallic film (see fig. 24), where the transparency lies in the violet and the opacity extends throughout the infra-red. The film of colloidal silver behaves like a turbid medium, which has the property of increasing in transparency with wave-length. This is in agreement with Garnett,[2] who concludes from the optical properties of Cary Lea's so-called solutions of allotropic silver that they consist of small spheres of silver, *i.e.*,

[1] Cary Lea's Allotropic Silver, Amer. Jour. Sci., vol. **37**, p. 746, 1889.

[2] Garnett: Proc. Roy. Soc. (A), **76**, p. 370, 1905–06; Phil. Trans., A, pp. 385–420, 1904.

normal silver in a finely divided state, little if any being in true solution (molecularly subdivided). He further concludes that the color of ruby gold glass is due primarily to the presence of small spheres of gold; the irregular blue and purple colors, sometimes exhibited by gold glass, are then explained by the presence of crystallites (caused by the coagulation of gold spheres) which reflect but do not transmit red light.

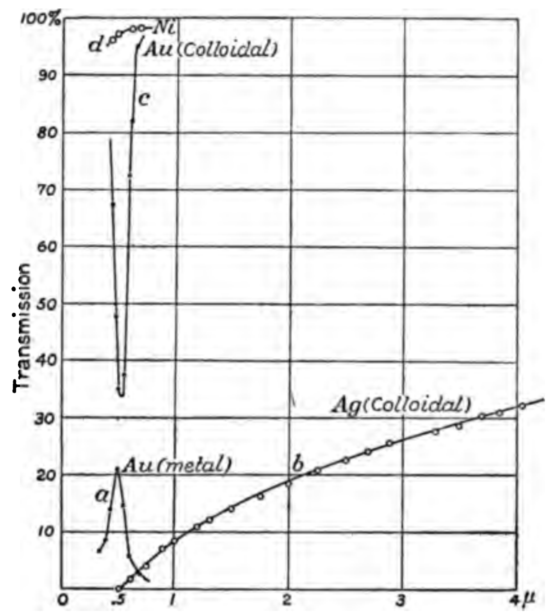


FIG. 36. — Gold; Silver; Nickel.

In view of the fact that colloidal metals appear to behave exactly the reverse of films of a metal in the normal state, the subject deserves further consideration.

GOLD AND NICKEL.

In fig. 36, curve *a* gives the transmission (Hagen and Rubens, *loc. cit.*) of a metallic film of gold, which has the well-known transmission band in the yellowish-green part of the spectrum. Curves *c* and *d* give the transmission of suspensions, in water, of colloidal gold and nickel, respectively, studied photometrically by Ehrenhaft.[1] The gold transmitted red, while nickel (also Pt and Co) have a brown color by transmitted light. As in the present work, the behavior of the colloidal material is exactly the reverse of the normal metal film, thus placing it under the class known as non-metals or "insulators."

[1] Ehrenhaft: Ann. der Phys., 11, p. 489, 1903.

GROUP IV: TRANSMISSION SPECTRA OF COLORED GLASSES.

Cobalt Glass.

(Fig. 37. Thickness, 2.43 mm.)

Colored glasses have been but little studied. Nichols[1] examined cobalt glass, and found an absorption band at 1.4 μ. This is one of the few substances having a prominent band near the visible spectrum. Garnett (*loc. cit.*) concludes that the deep blue color of cobalt glass can not be due to small diffused spheres of metallic cobalt, which would give a reddish color to transmitted light, but that the metal is in the form of discrete molecules (amorphous).

For the present work a fluorite prism and bolometer were used (see Appendix II).

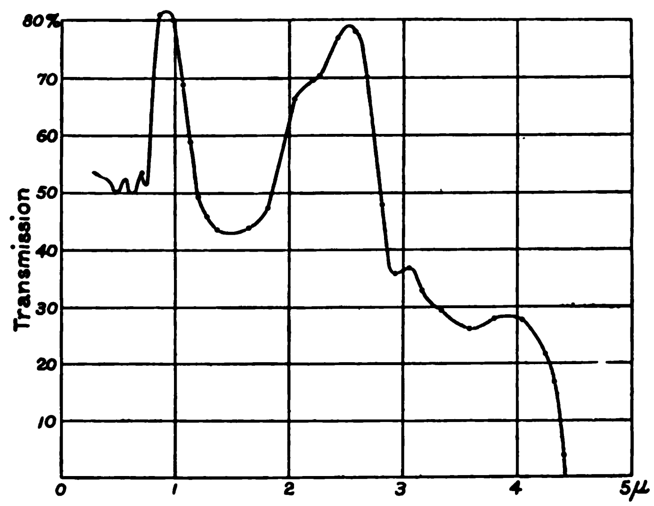


Fig. 37. — Cobalt blue glass.

In fig. 37 is given the transmission curve of a cobalt blue glass which showed three weak absorption bands in the visible spectrum. In the infra-red there is a larger absorption band at 1.5 μ, a smaller band at 2.1 μ, and second large band at 3.5 μ. The small band at 3 μ is due to the glass itself, and is also found in quartz. Beyond 4 μ the opacity is due to the glass, as found in clear specimens.

The behavior of this glass is entirely different from the red glasses to be noticed on a following page. It is not like an optically turbid medium, unless we consider it to have more than one region of selective absorption, which is in line with the conclusion arrived at by Garnett (*loc. cit.*).

[1] Nichols, E. F.: Phys. Rev., 1, p. 1, 1893.

Blue-violet Glass.

(Schott's[1] No. F 3086; $t=2.58$ mm.)

In fig. 38 is given the transmission of a plate of blue-violet glass. There is a large absorption band at 0.5 to 2 μ, followed by smaller bands at 2.1 and 3.5 μ. In the deep infra-red such a band would cause selective reflection. In the present case the absorption band is due to the metal behaving somewhat like an optically turbid medium. Using a pocket spectroscope close to a Nernst glower, it was found that a trace of yellow

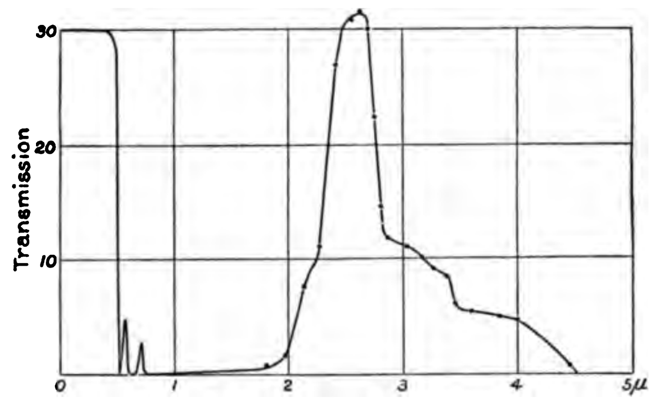


Fig. 38. — Blue-violet glass.

at 0.56 μ and of red at 0.707 μ was transmitted, the intensity of the maxima being of the order of 0.01 per cent. In the violet the transmission was 30 per cent. This region was studied with a spectrophotometer. Ångström has very ingeniously applied this glass in measuring the violet radiation from the sun; using an absorption cell of water, 1 cm. thick, in addition to this glass plate, all the radiation beyond 0.5 is absorbed.

Green Glass.

(Schott's copper oxide, No. 431 III. Fig. 39. Thickness $t=3.43$ mm.)

The specimen examined showed an absorption band in the violet and a second one in the red. There appears to be a small band at 2 μ, beyond which point there is the usual absorption of uncolored glass. The band at 2.95 μ, found in silicates, *e.g.*, mica, seems to be intensified by the presence of coloring substance, while the transmission seems to be terminated at a shorter wave-length (also due to the coloring substance) than would be found in a clear plate of glass of the same thickness.

Ruby Glass.

(Fig. 40. Curve *a*, Schott's monochromatic red, No. 2745; $t=3.18$ mm. Curve *b*, impure red; $t=2.48$ mm.)

The monochromatic red glass examined is used in the Holborn and Kurlbaum pyrometer. The second sample, curve *b*, transmitted impure

[1] See Zsigmondy, Zs. für Instrk., 21, p. 97, 1901.

red; it was taken from a Le Chatelier pyrometer and is described as a copper oxide glass. Although thinner, the second sample is the more opaque in the region of 1 to 2.5 μ. The transmissivity of the monochromatic red glass is very unusual. In the region of 1 to 2.5 μ the metal which is used to color the glass renders it more permeable to heat waves than is ordinary, visually transparent glass. The band at 2.9 μ appears to be intensified by the presence of the metal, which behaves like the

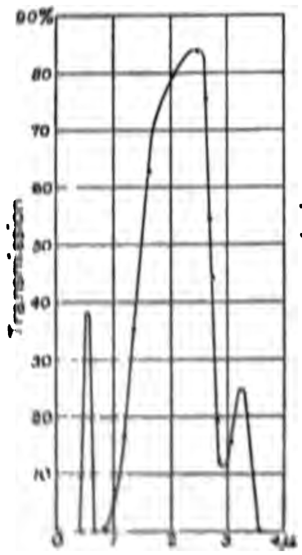


Fig. [illegible] Green glass.

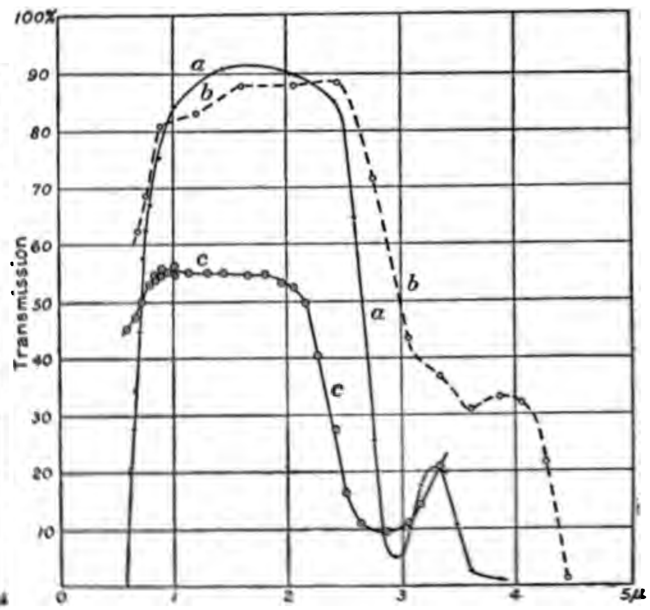


Fig. [illegible] — Ruby glass (a) and (b); Sphalerite.

colloidal suspensions just mentioned. In fact, it is a pertinent question whether the red color in glasses is due to the presence of metals, such as copper and gold, in the colloidal condition. The monochromatic red glass was found to have a uniform reflecting power (about 4 to 5 per cent) throughout the spectrum to 8 μ. This seems to show that the transparent region at 1 to 2 μ is not due to the same cause that produces an abnormal transparency on the short wave length side of a region of anomalous dispersion.

Black Glass.

(Fig. [illegible] Curve a, [illegible] mm; curve b, Schott's Rauchglas No. 444 III, $t = 2.0$ mm.)

Curve a gives the transmission of a dark "neutral" glass colored with the oxides of cobalt and nickel. This glass has a uniform absorption throughout the visible spectrum. There are small absorption bands at [illegible] and [illegible] μ, respectively. Curve b gives the transmission of a very dark glass, which shows an absorption band in the region of [illegible] μ.

Considered as a whole, these glasses can be divided into two groups.

viz, (1) glasses having absorption bands in the visible and in the infra-red spectrum, and (2) glasses having a wide absorption band in the optical region, followed by an increase in transparency with wave-length. The red glasses belong to the latter group, and their behavior is more nearly like that of optically turbid media, the color being due to the presence, in the glass, of small spheres of metal (see Garnett, *loc. cit.*). To the first group belong the cobalt blue and Schott's blue-violet glass. If the color in some glasses is due to the metal, one would expect great opacity in the infra-red, as is known for a thin film of the metal. If the metal is present in a colloidal form, the present examination of colloidal silver would indicate great transparency, with the possibility of small absorption bands in the infra-red. The whole question is in an unsettled state, and an investigation of the transmission of various glasses, blown into thin films, as described in Carnegie Publication No. 65, page 65, seems highly desirable.

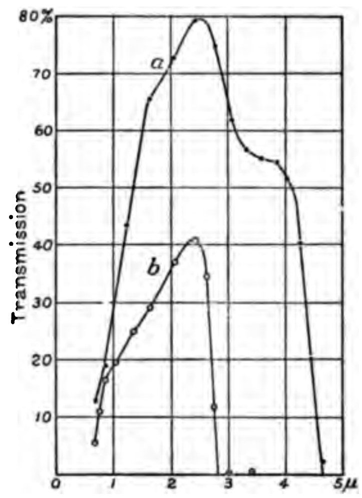


FIG. 41. — Black glass.

In leaving this subject it is of interest to note that a specimen of garnet (Carnegie Publication No. 65, p. 59) was found to have a wide absorption band, with complete opacity extending from 1.2 to 2.6 μ. This is one of the few substances having a large absorption band near the visible spectrum.

SPHALERITE (ZnS).

(Cleavage piece; $t = 1.53$ mm.; transparent; slight yellowish tinge; curve *c*, fig. 40.)

This substance was previously examined (Carnegie Publication No. 65, p. 63), using for the purpose a rock-salt prism and a radiometer. In the present examination, the same mirror spectrometer, but a fluorite prism and a bolometer were used. On account of the small dispersion at 1 μ the rock-salt prism is not well adapted for work in this region. The transmission curve of sphalerite appears to have a band at 1.8 μ. On examination of the original data and curves, it appears that in redrawing the curve for publication the draftsman placed the point at 1.3 μ a little too high (should read 59 per cent), which in the reduced illustration makes a depression at 1.8 μ.

The curve obtained with the fluorite prism is given in fig. 40, and represents conditions more accurately. A Nernst glower was used as a source, which gave large deflections in this region of the spectrum.

The transmission curve increases uniformly from 47 per cent at 0.6 μ to 56 per cent at 1 μ, then decreases uniformly to 54 per cent at

1.8 μ, beyond which the transmission drops rapidly to a minimum at 2.9 μ, previously found. Using this larger dispersion, there appear to be no absorption bands up to 1.9 μ. The study of zinc sulphide is of interest in connection with luminescence of one form of this substance known as Sidot blende. In their study of the rapidity of decay of phosphorescence in Sidot blende, when subjected to infra-red rays, Nichols and Merritt[1] found that the rate of decay was the most rapid when exposed to infra-red rays of wave-length 0.9 μ and of wave-length 1.37 μ. From this it would seem that the screen of Sidot blende possessed broad absorption bands with maxima in the region of 0.9 μ and 1.37 μ. The luminescence of Sidot blende appears to be due to some metal dissolved in it. From the foregoing experiment on sphalerite (ZnS) it appears that these absorption bands are not due to the ZnS, but rather are to be sought for in the dissolved metal (see cobalt glass), and in the cement, in case a glue is used to secure the powder in the form of a "screen." The present study of colored glasses gives us some idea of what to expect in solutions of metals (oxides of metals?) in glasses; while the phenomenon may be further complicated by the molecular structure of ZnS, which in the form of Sidot blende may have absorption bands not found in sphalerite.

[1] E. L. Nichols and E. Merritt: Phys. Rev., 25, p. 362, 1907.

CHAPTER II.

EFFECT OF SPECIAL GROUPS OF ATOMS OF RADIANT ENERGY.

In the present chapter it is purposed to discuss some of the relations found among the infra-red spectra of the various substances examined; and incidentally to explain some apparently inconsistent statements made in Part I on the effect of certain particular groups of atoms in producing characteristic absorption bands.

COMPARISON OF ULTRA-VIOLET AND INFRA-RED.

Hartley[1] found that an open chain of CH-groups, as well as a union of C and N atoms, produced no absorption bands in the ultra-violet. Neither could he identify any absorption band, of any of these substances, with the carbon atom in the benzene ring; the molecules behaved as though there were no special atoms present. This is just the opposite of what was found in the infra-red. But the length of the infra-red spectrum examined is 60 times as long as the ultra-violet. It is, therefore, possible to find relations in the infra-red which, on account of the narrowness of the spectrum, may not be found in the ultra-violet. In the infra-red there are transparent regions between characteristic absorption bands, which are often several times the width of the entire ultra-violet spectrum. The petroleum distillates (chain compounds) have a wide transparent region between 4 and 5 μ, just as Hartley found in the ultra-violet. In general, if we were to examine a narrow region of the spectrum, *e.g.*, the ultra-violet, or at 4 μ in the infra-red, it appears to be a matter of chance whether or not absorption bands will be found there. In the visible spectrum many substances have absorption bands, *i.e.*, are colored. If the eye were sensitive to rays of wave-lengths 3 to 3.5 μ, all the carbohydrates would appear "colored," and the position of the maximum of the absorption band would be just as irregular as those found in the visible and in the ultra-violet spectrum.

THE HYDROXYL GROUP.

During the preparation of the third volume of Kayser's "Handbuch der Spectroscopie" only the writer's "Preliminary Report on Infra-Red Absorption Spectra"[2] was available to the compilers. They call attention to the fact that "the writer found an effect due to special groups of atoms, particularly OH and CH_2. Although many substances, which contain the

---

[1] Kayser: Spectroscopy, 3, p. 169 and p. 170.

[2] Coblentz: Astrophysical Journal, 20, 207, 1904.

OH-group, have an absorption band between 2.9 and 3 μ, Coblentz questions whether they are due to the OH-group. On the other hand, he thinks the CH_3-group causes the band at 3.43 μ."

This inconsistency is easily explained. One need but examine the third volume of Kayser's Spectroscopie, pages 81, 83, 84, 88, 283, etc., and see the numerous exceptions to "Kundt's Law," to be convinced that the announcement of that "Law" was premature. Knowing how subsequent investigators were misled by this announcement, it seemed to the writer that, so long as there were any serious exceptions, the effect of special groups of atoms on heat-waves should be doubted until the evidence was much greater than obtained at that time. The mineral brucite [$Mg(OH_2)$] caused this doubt; for if there is an effect due to the OH group, one would expect to find it in such a simple compound as this one. The first examination of brucite showed no band at 3 μ, but a wide band with a maximum at 2.6 μ. Since then this mineral has been re-examined, using a larger dispersion, and the large band was resolved into its components, with maxima at 2.5, 2.7, and 3 μ. In other words, this mineral has the characteristic band of the hydroxyl group. In the meantime, numerous other substances (see Carnegie Publication No. 65) containing OH-groups and water of crystallization have been examined. In Carnegie Publication No. 65, the exceptions to the rule that the OH-group has a characteristic absorption band at 3 μ were found among minerals of which the chemical constitution is in doubt. The absorption band at 3 μ, found in substances containing hydroxyl groups, is, therefore, to be ascribed to that group of atoms. The band at 3 μ found in the alcohols belongs, therefore, to the OH-group, and one ought not expect (as the writer stated in Carnegie Publication No. 35, p. 108) to find a second band at 6 μ (which is found in water), if the 3 μ band is due to the OH-group. The OH group apparently does not produce a harmonic series of bands such as are to be found in compounds containing CH_2 or CH_3-groups. Water also has a harmonic series of bands, but it has not yet been shown to be due to the OH-group.

THE EFFECT OF MOLECULAR WEIGHT OF THE MAXIMA.

In Part I a search was made for a shifting of the maximum of an absorption band with an increase in the number of atoms, or especially of groups of atoms, in the molecule. The evidence was very contradictory. In the case of the methyl derivatives of benzene, the maximum of the band was found at 3.25 μ in benzene, at 3.3 μ in toluene ($C_6H_5CH_3$), at 3.38 μ in the xylenes [$C_6H_4(CH_3)_2$], and at 3.4 μ in mesitylene [$C_6H_3(CH_3)_3$]. In other words, by substituting three CH_3-groups for an H atom, we have shifted the maximum from 3.25 to 3.4 μ. Several gases showed a shift of the band, in the region of 3.2 to 3.5 μ, toward the long wave-lengths with an increase in the number of H atoms. On the other hand, several nitrogen

derivatives of benzene showed a shift of the maximum toward the short wave-lengths. An examination of two petroleum distillates, C_8H_{18} and $C_{24}H_{50}$, showed no shift of the maxima, and on the whole the evidence of a shift, due to a change in molecular weight, was inconclusive.

In Carnegie Publication No. 65, p. 56, the sulphates showed absorption and reflection bands which seemed to shift toward the long wave-lengths with increase in molecular weight. This data will be discussed in the present paper.

Ever since the announcement of "Kundt's Law" various observers have tried to find relations among the absorption bands, viz, such that with an increase in molecular weight the band shifts toward the long wave-lengths. The results have just been discussed in the first part of this chapter. There is a physical basis for expecting a shift of the band with change in molecular weight. For example, the sulphate of the metals K, Rb, and Cs have been compared by Tutton,[1] who has shown that both as regards crystalline form, specific gravity, thermal expansion, and corresponding refractive indices the Rb salt lies between the K and Cs salts.

In Carnegie Publication No. 65, the sulphates of Mg, Ca, Sr, Cd, and Ba were found to have the maximum of their absorption at 4.5, 4.55, 4.6, 4.6, and 4.63 μ, respectively. The same shifting of the maximum was observed in the reflection bands of $SrSO_4$ and $BaSO_4$; in the former the maxima are at 8.2, 8.75, and 9.05 μ, while in the latter the maxima are shifted to 8.35, 8.9, and 9.1 μ.

In the present paper all the available data have been compiled, to show this shift. In fig. 42 is given a composite of the reflection curves of the carbonates [(Mg, Ca, Zn, Ba, Pb) CO_3] described on a previous page. The maxima are evidently double, although it is not very apparent in some curves. As a whole, however, the location of the maxima of $PbCO_3$ is so much farther in the infra-red than in $MgCO_3$ that there can be no doubt that the shift is a real one.

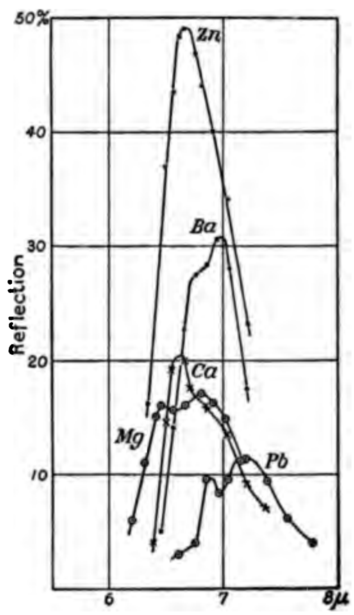


FIG. 42. — Reflection curves of carbonates.

In fig. 43 are given the graphs of the maxima of the *reflection* band plotted against atomic weight of the basic atom in the molecule. The carbonates of Mg, Ca, Zn, Sr, Ba, Fe, Cu, Pb are included. In this figure the two maxima of the complex band at 6.4 to 7.2 μ are plotted. When the

[1] See Miers's Mineralogy.

maximum is not sharp and well defined, several readings were made and plotted in the figures. This method of reading a flat band establishes a limit within which the maximum may lie. The two graphs are approximately parallel, and show a uniform shift of the maxima of Mg, at 6.55 and 6.86 μ to 6.94 μ and 7.18 μ, respectively, in Pb. The carbonates of Fe

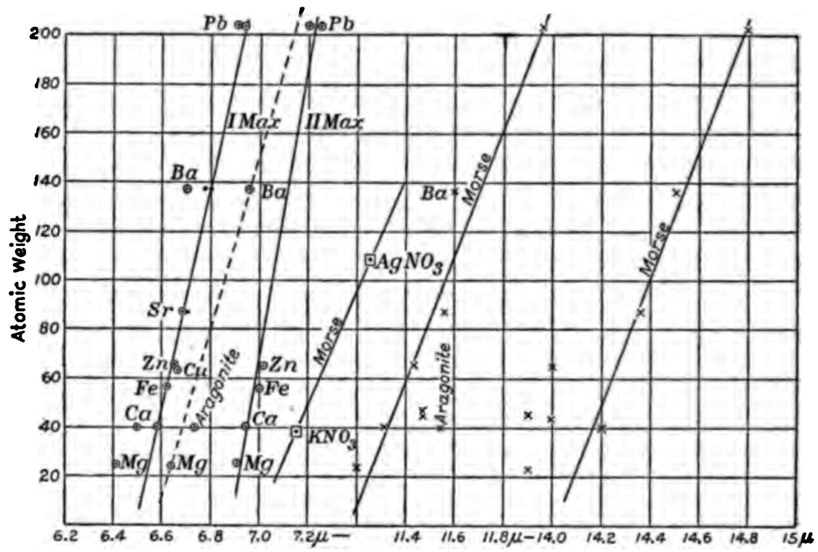


Fig. 43. — Maxima of reflection bands of carbonates.

and Cu lie farthest from the curves; but they belong to a different group in Mendelejeff's table. The graphs at 11 μ and 14 μ are due to Morse, see Appendix III.

In fig. 44 are plotted the maxima of the *reflection* bands of the sulphates [(H_2, Mg, Ca, Sr, Ba)SO_4], previously examined (Part IV). Here there are

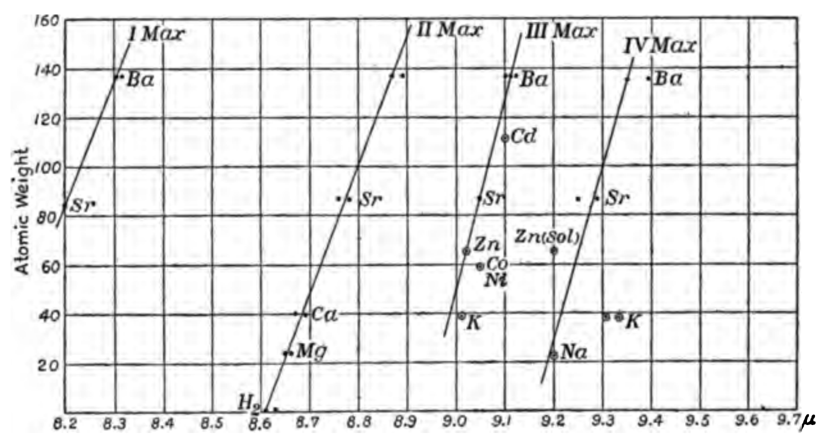


Fig. 44. — Maxima of reflection bands of sulphates.

four bands. As in the preceding, several readings of each ill-defined band are plotted in order to get the limits between which it extends. It is of interest to note that one of the H_2SO_4 bands, at 8.62 μ, falls on the graph of the second maximum.

In fig. 45, the maxima of the *absorption* bands of the sulphates [(Mg, Ca, Sr, Cd, Ba) SO_4] are plotted (see Part III, Carnegie Publication No. 65, for data). It will be noticed that the graph of the band at 4.5 μ is much steeper (the horizontal scale is different for these bands) than are the ones farther toward the infra-red. The maxima of the absorption bands lie close to the graph drawn through them.

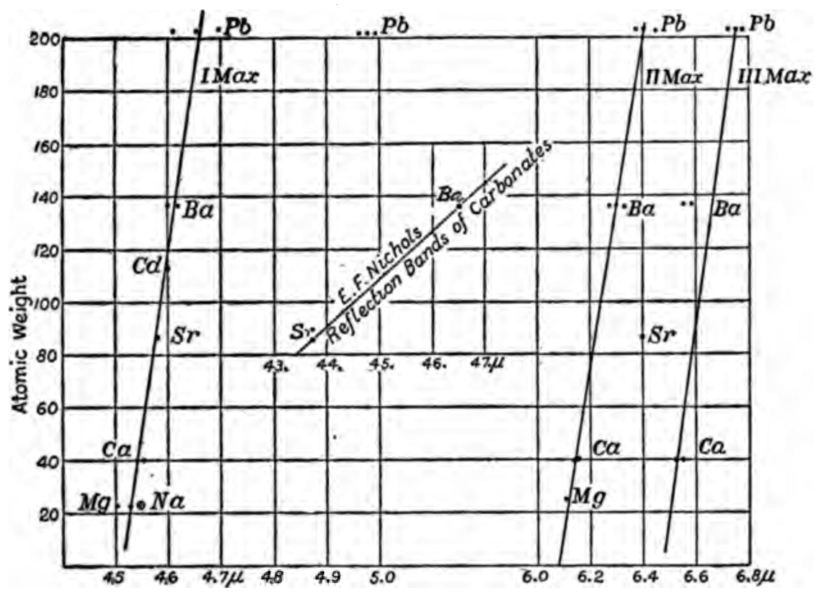


FIG. 45. — Maxima of absorption bands of sulphates.

The second and third maxima of the absorption bands at 6.2 and 6.5 μ are quite close to the graph, except $SrSO_4$, which has but one maximum lying midway between the two graphs. From this it would appear that the $SrSO_4$ band may be the mean of two unresolved bands (see, however, Part V, Chapter III). The slant of these graphs is less than in the preceding one.

For a discussion of the graph at 45 μ see Appendix III.

Considered as a whole, the data presented demonstrate very conclusively the influence of the molecular weight of the basic atom or "ion" upon the position of the maximum. The results explain why the increase in the number of the *groups* of atoms (see carbohydrates) had no effect upon the position of the maximum. This is to be expected if the *cause* of the band is due to the group of atoms; but the *position* of the band

depends upon the metallic (basic) atom to which the group of atoms is united to form a compound.

It is a remarkable fact that nearly all the substances examined, especially the oxides, have a region of strong selective reflection from 8 to 12 μ. Drude[1] has shown that the optical properties (*e.g.*, dispersion) lead to the conclusion that each atom is a union of many independently vibrating elementary masses or ions. In the ultra-violet the absorption band is due to the sympathetic vibration of particles which have a charge and a mass identical with the negative ion or "electron," while in the infra-red the absorption and reflection bands are due to positive ions ("ponderable atoms") which have a mass of the order of magnitude of the atom. From this standpoint, one would expect to find a shift of the maximum toward the long wave-lengths, as we increase the atomic weight of the element which is attached to the radical.

The latest theoretical discussion of this subject is due to Einstein,[2] who shows how the theory of radiation, especially Planck's, leads to a modification of the molecular-kinetic theory of heat, and clears up points heretofore difficult. He also shows relations between the thermal and optical properties of solid bodies.

TABLE II.

Element.	Atomic heat = atomic weight × specific heat.	λ calculated.	Substance.	λ observed.	λ calculated.
		μ		μ	μ
S and P.....	5.4	42	CaFl	24; 31.6	33; >48
Fl..........	5	33	NaCl	51.2	>48
O..........	4	21	KCl	61.2	>48
Si..........	3.8	20	$CaCO_3$.....	6.7; 11.4; 29.4	12; 21; >48
B..........	2.7	15	SiO_2.......	8.5; 9.0; 20.7	20; 21
H..........	2.3	13			
C..........	1.8	11			

From the value of the atomic heat of a substance, he computes the maxima of the bands of infra-red selective reflection. The observed reflection bands and the same as calculated by Einstein are given in table II. From this table it will be seen that carbon (diamond) would have a large reflection band at 11 μ, which is possible, as will be noticed in the transmission curve, fig. 30.

This table shows that certain calcite maxima are due independently to C at 11.4 μ and to O at 21 μ. In quartz the band at 20 μ is due to Si at 20 μ and O at 21 μ. From this line of reasoning, it would appear that the large reflection band of carborundum at 12.5 μ is due to C, and that there is another band at 20 μ due to Si. A similar computation for selenium and iodine indicates a reflection band at about 42 μ.

[1] Drude: Ann. der Phys. (4), **14**, 677, 1904.
[2] Einstein: Ann. der Phys. (4), **22**, p. 181, 1907.

CHARACTERISTIC BANDS OF QUARTZ AND OF SILICATES.

About half the minerals known are silicates. Their percentage composition has been ascertained by quantitative analysis, but little has been possible, as yet, in establishing their constitutional formulæ. In organic chemistry the constitution of compounds has been determined by vapor density determinations, by the preparation of series of derivatives, by the replacement of certain constituents by organic radicals, or by studying their physical properties in solution. In mineralogy this has, as yet, not been possible, and the constitution of many of the minerals has been derived mainly from analogies with other substances which are better understood. The silicates are sometimes grouped as follows: *disilicates* (RSi_2O_5) are salts of disilicic acid ($H_2Si_2O_5$), and have an oxygen ratio of silicon to bases of 4:1; *polysilicates* ($R_2Si_3O_8$) are salts of polysilicic acid ($H_4Si_3O_8$), with oxygen ratio of 3:1; *metasilicates* ($RSiO_3$) are salts of metasilicic acid (H_2SiO_3), oxygen ratio of 2:1; *orthosilicates* (R_2SiO_4), salts of orthosilicic acid (H_4SiO_4), oxygen ratio of 1:1.

Among the complex silicates, and often among the simple ones, not only is the actual molecular structure in most cases doubtful, but even the simple empirical composition of many species is still unsettled. A single species may vary greatly in composition. This has been explained by regarding the different forms as derivatives of a normal salt in which various atoms or molecular groups may enter. It is not surprising then, in the present limited study of their reflection spectra, to find no very important relations among the reflection bands of silicates.

From previous work it is difficult to decide what one ought to expect in the question of the coincidence of bands in SiO_2 and in silicates. In the case of the carbonates there are no bands (except a small depression at 4.6 μ in common with CO) coincident with those of CO_2; and we might expect a similar condition to obtain in the silicates and SiO_2. On the other hand, in the carbohydrates having a structure indicating CH_2 and CH_3 groups, there is a coincidence of certain characteristic bands with those of ethylene (C_2H_4) and ethane (C_2H_6). The introduction of oxygen atoms, however, modifies the spectrum, and, as a rule, there is no longer a coincidence with the former bands. Furthermore, in SO_2 the maximum at 8.7 μ is in coincidence with a similar band found in many sulphates, while the band at 10.4 μ is in common with a similar one in fuming sulphuric acid and is probably due to SO_4. From this it is difficult to predict what one ought to expect in the case of SiO_2 and of the silicates. From previous observations that groups of chemically-related substances have similar absorption spectra, one would expect to find a similar condition to obtain in the various groups of silicates. The present investigation is not extensive enough to draw general conclusions. Moreover, the constitution of the minerals is in many cases in doubt, so that the lack of similarity in

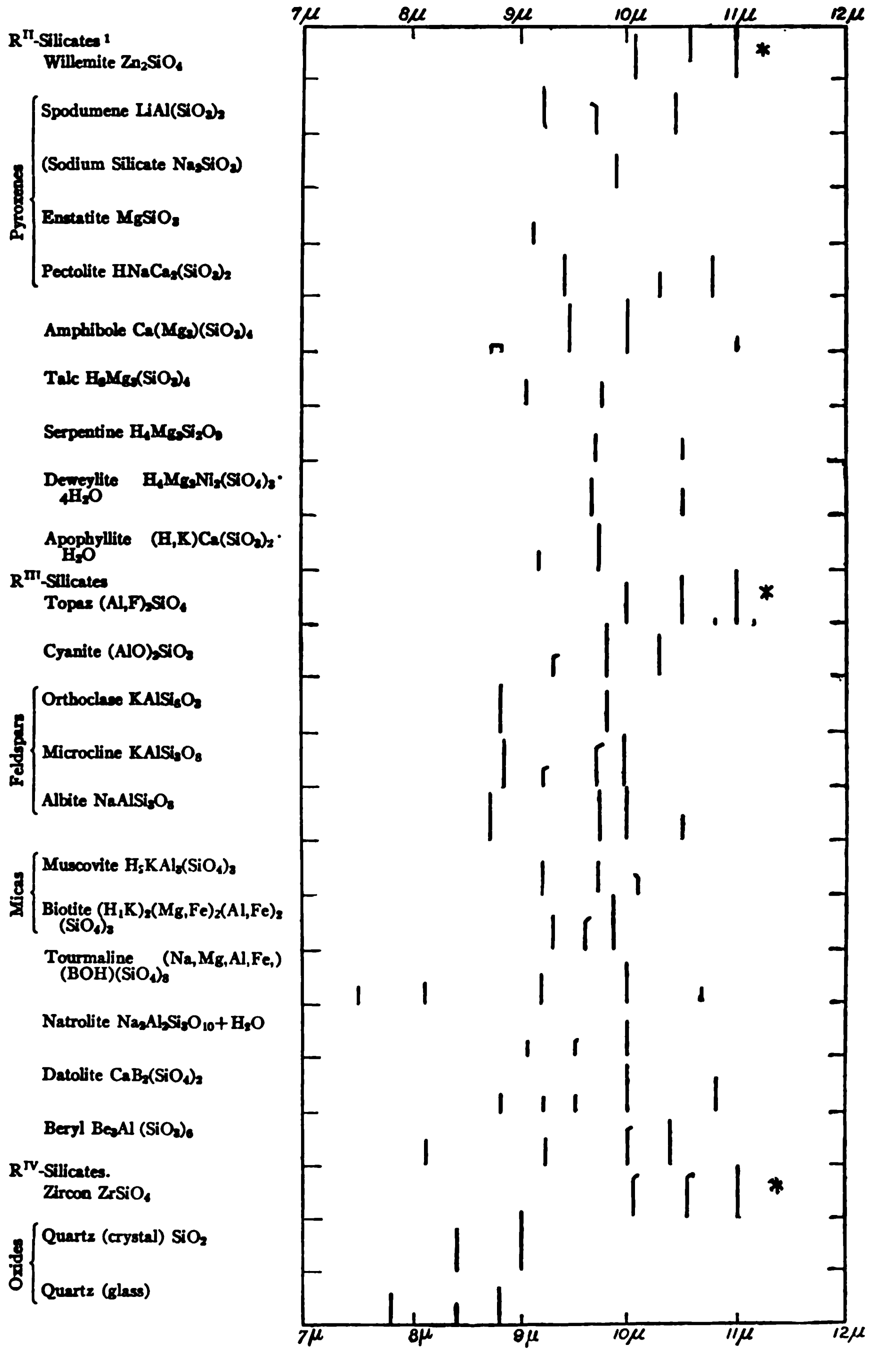


Fig. 46. — Line spectra of silicates.

---

[1] R^{II}, Valence of metal is indicated by the exponent.

spectra of supposedly related silicates is not due to a fault in the criterion for judging such relations. The reflection bands of the various silicates examined are represented by lines in fig. 46. The lines broken at the top indicate that the reflection bands are not well resolved. The silicates of the divalent metals, R^{II}-silicates, are metasilicates, while the R^{III}-silicates are orthosilicates, as noticed on a previous page. Since there is a band (at 10 μ) in common with both groups we are at liberty to assume that the division into ortho- and meta-silicates is not a characteristic in the spectra. Again, the groups of chemically related minerals may or may not have similar spectra. Thus, the pyroxenes and micas have dissimilar spectra. Serpentine and deweylite (and the feldspars) have similar spectra. Orthoclase and microcline, which are isomeric, show their structure by their dissimilar spectra. The amphibole seems out of place. Spodumene, talc, serpentine, deweylite, apophyllite, microcline, albite, and muscovite have a group of atoms in common, which causes a band at about 9.7 μ. Amphibole, topaz, microcline, albite, tourmaline, natrolite, datolite, and beryl have a group of atoms causing a band at 10 μ.

Serpentine, deweylite, topaz, and albite have a common radical causing a band at 10.5 μ. Quartz glass, datolite, orthoclase, and possibly amphibole, have a band in common at 8.8 μ.

The group of triplets in willemite, topaz, and zircon is unusual, the maxima being, on an average, at 10.1, 10.6, and 11 μ, respectively. In willemite (R^{II}) the bands are sharp and well defined, in topaz (R^{III}) the bands are not so well resolved, while in zircon (R^{IV}) the bands are almost indistinguishable. Whether this change in sharpness of bands is due to the variation in valence is a pertinent question. Previous work indicates that the variation in the sharpness of the bands is due to the amount of oxygen present — oxygen sharpens the bands. In crystalline quartz and

TABLE III.

Compounds having the following groups.	Show characteristic absorption and reflection bands at:						
	μ	μ	μ	μ	μ	μ	μ
CH_2 order CH_3	3.43	6.86	13.6 to 13.8	14			
NH_2	2.96	6.1 to 6.15					
C_6H_6	3.25	6.75	8.68	9.8	11.8	12.95	
NO_2	7.47	9.08 ?					
OH	2.95	(3.0)					
NCS	4.78						
$R-SO_4$[1]	4.55	6.1	6.5	8.2	8.7	9.0	9.2
R–SiOx	3	8.4	8.8	9.7	10	10.5	11
$R-CO_3$[1]	6.5	6.8	11.4	14	29.4		

[1] The position of the maxima in these compounds depends upon the atomic weight of the basic element, R, with which the group or acid radical is combined.

quartz glass there is a band in common at 8.4 μ, showing a common group of atoms. This band, with the five groups in common with the silicates, makes a total of six groups of bands, the radicals which cause them being, as yet, undetermined. These bands are at 8.4, 8.8, 9.7, 10, 10.5, and 11 μ. This seems to substantiate the view expressed in Carnegie Publication No. 65, p. 95, that in the silicates there appear to be several silicon-oxide radicals, one or more of which are present in each mineral, or even in the different specimens of the same mineral.

In table III are given the characteristic maxima of the reflection and absorption bands of radicals studied in this and in previous work.

PART VII.

INFRA-RED EMISSION SPECTRA.

CHAPTER I.

EMISSION SPECTRA OF METALS IN HYDROGEN.

In Carnegie Publication No. 35 the writer presented the results of an examination of the arc spectra of various metals. It was there shown that only the alkali metals have strong emission lines in the infra-red. In the case of metals like copper, iron, and zinc there was a weak continuous spectrum in the region of 2 to 3 μ, which appeared to be due to the hot oxides formed in the arc. If this be true, then one would expect to eliminate this radiation by producing the arc in an atmosphere of hydrogen. During the past year (1907) this work has been repeated, using an arc inclosed in a metal case which was filled with hydrogen. A Rubens thermopile was used to measure the radiation. The galvanometer had a full period of 16 seconds; its sensitiveness was $i = 1.7 \times 10^{-10}$ for a scale at 1 m. When used with the thermopile the temperature sensitiveness was such that a deflection of 1 mm. $= 1 \times 10^{-5}$ ° C. for a scale at 1 m.

The spectrum was produced by means of the rock-salt prism and mirror spectrometer (slits 0.5 mm.) which were described in Carnegie Publication No. 65.

(*a*) NICKEL ARC IN HYDROGEN.

With this outfit the emission spectrum of nickel in hydrogen was examined. The window of the metal case inclosing the arc was of thin glass which absorbed all the radiation beyond 3.5 μ. The metal electrodes were about 1 cm. diameter, with the ends cut wedge-shaped. This produced a long narrow arc, an end-on image of which was projected upon the spectrometer slit by means of a 12 cm. focus, concave mirror.

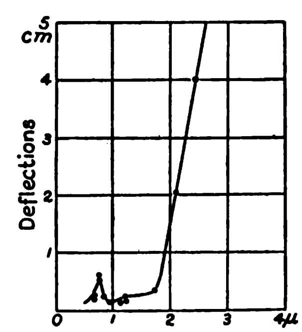


Fig. 47. — Nickel arc in hydrogen.

The spectrum appeared continuous in the red, where the maximum radiation was observed. The results are shown in fig. 47, where a strong emission is to be observed at 0.75 μ. Beyond 2 μ the radiation from the hot electrodes is indicated by the rapid rise in the radiation curve.

The results show but little radiation in the region of 2 μ, where previously a continuous spectrum was observed. It is also to be observed that no strong emission lines occur at 1 μ, where the alkali metals have intense lines.

(b) SPARK SPECTRA OF METALS IN HYDROGEN.

For producing a high potential spark (arc) a 10,000-volt transformer, with 100 volts, 1 to 9 amperes in the primary, was used. From one to three glass condenser plates, each having a capacity of 0.0028 M.F., was placed in parallel with the electrodes. This produced a very intense arc. An image of the electrodes was projected upon the spectrometer slit by means of a short focus, concave mirror. The electrodes were about 3 mm. diameter, filed wedge-shaped. They were mounted in glass holders which were fitted into a glass vessel of about 200 c.c. capacity by means of ground joints (designed by Dr. Nutting), which permitted adjustment of the electrodes as shown in fig. 48. The radiation passed through a quartz window about 3 mm. thick, hence opaque beyond 4 μ. The hydrogen was prepared electrolytically in an automatic glass generator shown in fig. 49.

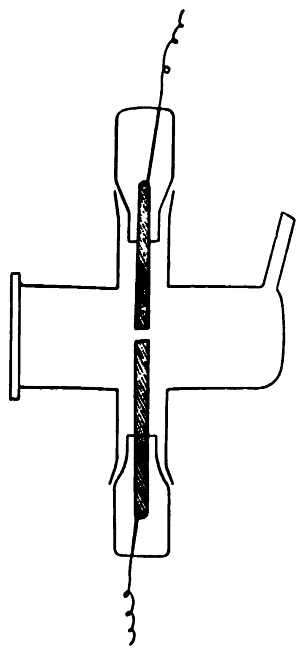


FIG. 48. — Hydrogen spark tube.

The spark (arc) spectra of the following metals were examined: aluminum, copper, and calcium. For electrodes of the latter, thin pieces were sawed from a large bar of the metal, which were then hammered into wires about 2 to 3 mm. in diameter. These were kept under oil to prevent oxidation. The result of the examination was rather disappointing, for no appreciable radiation could be detected up to 3.5 to 4 μ, where the electrodes gave from 3 to 10 cm. deflections. This latter was eliminated by covering the spectrometer slit over the whole length, except about 2 mm., which permitted only the radiation from the high potential arc (spark) to enter the instrument. The fact that no deflections greater than 1 mm. were observed is not due to a lack of sensitiveness of the instrument, and it may be concluded that no emission lines were produced which had an appreciable intensity. This is rather surprising, for calcium is close to the group of elements having emission lines in the infra-red.

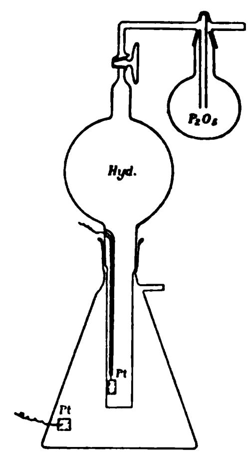


FIG. 49. — Automatic electrolytic hydrogen generator.

EMISSON SPECTRUM OF THE CARBON ARC.

The emission spectrum of carbon was previously examined by the writer in connection with the emission spectra of metals and salts of metals in the carbon arc. It was found that the *violet* part of the carbon arc had several emission lines near 1 μ, followed by a weak continuous spectrum with a maximum at about 2.5 μ. There seemed to be a slight emission band at 4.52 μ, which on subsequent examination could not be reproduced. The writer, therefore, concluded that in the combustion of the carbon electrodes no CO_2 or CO is formed, but that the carbon passes off as a vapor.

Furthermore, it was found that when salts of the alkali metals (Na, K, Li) were present, even in small quantities, there was a strong emission line at 4.52 μ.

The radiometer used was not very sensitive, while the conclusion that the carbon arc was mainly vapor of carbon did not seem satisfactory, hence the work was repeated, using electrodes of ordinary gas carbon and also of pure Acheson graphite. The latter is difficult to burn even when the length of the arc is only 2 mm. long.

In the present examination a Rubens thermopile was used. The galvanometer period was 10 seconds, and its sensitiveness was about 2.5×10^{-10} amperes. The spectrometer slit was 0.1 mm. wide and 2 mm. long, and an image of the blue vapors of the arc was projected upon it by means of a short focus mirror. The carbon electrodes were of the usual diameter, 12 mm., while two sizes (5 and 10 mm. diameter) of graphite electrodes were used. An examination was also made using one carbon and one graphite electrode.

In fig. 50 are given the emission curves of the carbon arc, *a* and *b* for a solid electrode with soft core, using 15 amperes (D. C.), while curve *c* is for hollow electrodes (2 mm. holes). The latter was examined to learn whether the air, drawn in through the hole, had any effect — which appears negative.

In curves *d* and *e* are given the emission curves observed at various times, under various conditions, when the hollow carbons contained the salts of the metals NaCl and KCl. The length of the arc was from 5 to 7 mm. and in some instances was as much as 12 mm. On the whole, whatever the current — from 5 to 15 amperes — there is always an emission band at 4.5 μ when salts of the alkali metals are in the arc, while the pure carbon (on 15 amperes) had little if any selective emission in this region.

An examination was then made of the emission of pure graphite (Acheson's). The direct-current arc was maintained with difficulty and could not be made longer than 4 to 5 mm.

In fig. 51 are given the observed results for the emission of pure graphite

in the region of 4.5 μ. The purity of this material may be judged from the entire absence of the sodium lines; only the violet carbon bands were

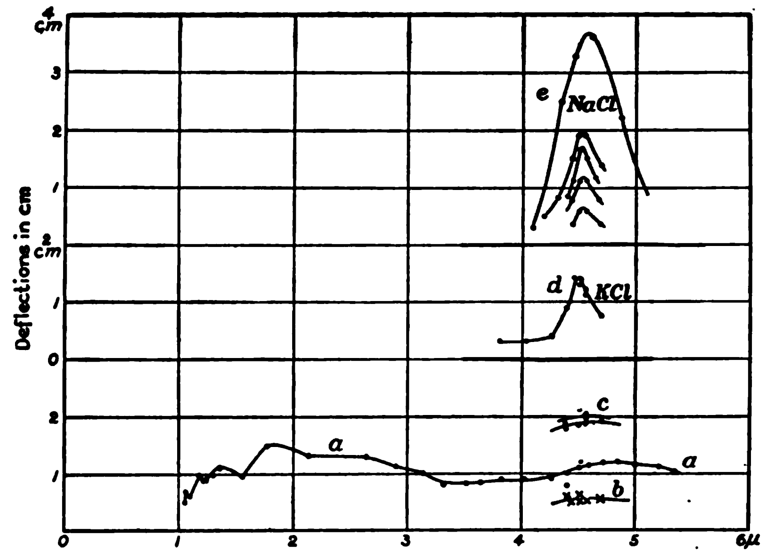


FIG. 50. — Emission of carbon arc.

visible. The lower curves are for a current of 7 amperes (120-volt circuit), while the two upper curves are for a current of 8 amperes, all of

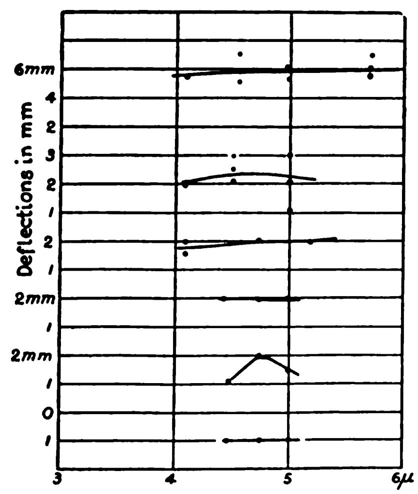


FIG. 51. — Emission of graphite arc (8 amperes).

which were obtained under various conditions. On account of the difficulty in maintaining a steady arc, no attempt was made to map a strong emission band extending from 1.2 to 1.7 μ and a second band extending

from 2 to 3 μ. The latter is the one always observed and generally attributed to oxides, in the case of a metallic arc.

It is to be observed that the deflections are only a few millimeters as compared with the large deflections when salts of metals are present.

An examination was then made of the graphite arc, using a current of 4 amperes. The length of the image of the arc projected upon the spectrometer slit (which was also the length of the arc itself) was only from 2 to 3 mm. The arc was very unsteady and difficult to keep burning. The results are given in fig. 52, curves *a* (4 amperes) and *d*. Curve *a* is for an arc-length of 2 mm., while *d* is for a length of about 5 mm. For the shorter arc the maximum is shifted toward the long wave-lengths.

In this same figure, curve *b* gives the emission when the cold (negative) electrode was a gas carbon (with soft core) and the positive electrode was pure graphite. The current was varied from 5 to 6 amperes, and the length of the arc was from 4 to 5 mm. There is an emission maximum at 4.6 μ, as was found for the two graphite electrodes. For comparison of position and intensity, the emission band of carbon dioxide in a Bunsen burner is given in curve *c*, fig. 52. The results with the pure graphite show that there is a sharp emission band at 4.65 μ (4.55 μ for a longer arc), where previously, for a larger current, there was none. Since all the observations extend over the same range of length of arc, it appears that the occurrence of the emission band depends upon the current and that it disappears for a large current. This is certainly extraordinary. Since the observations on graphite were made in quick succession on the same day, as given here, and since no changes were made in the apparatus, the lack of an emission band for a current of 7 amperes is not to be attributed to a fault in the adjustments. To attribute the occurrence of emission bands, when salts of metals are present, to some "catalytic" action caused by the presence of these metals does not elucidate matters very much.

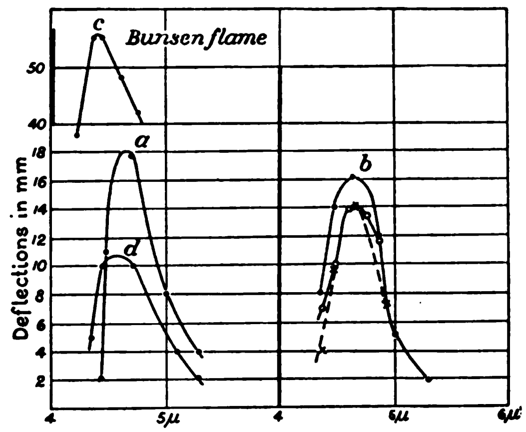


FIG. 52. — Emission of graphite arc (4 to 6 amperes).

Paschen was the first to observe that the emission band of carbon dioxide at 4.3 μ shifts to the long wave-lengths with rise in temperature. At that time the dissociation of carbon dioxide at high temperatures was but little investigated. Since the absorption band of carbon dioxide is at 4.3 μ and that of carbon monoxide is at 4.6 μ, if the emission band is due to a pure thermal effect, then one would expect to find that, with rise in

temperature and the consequent dissociation of CO_2 into CO, the maximum of the emission band of CO_2 will shift toward that of CO. The writer has observed this emission band of CO_2 under various conditions of temperature. In the emission spectrum of the Hefner lamp it was found at 4.36 μ. In the arc spectra of the salts of the metals previously studied it was found at 4.52 μ. In the vacuum-tube radiation of CO and CO_2 the maximum was found at 4.75 μ. In the acetylene flame it was found at 4.4 μ, while in the present examination it occurs at 4.55 to 4.65 μ. It has always appeared to the writer that this shift of the emission maximum with rise in temperature is due to dissociation of CO_2 into CO, and no satisfactory data has yet been found to refute this assumption. The vacuum-tube radiation of CO and CO_2, where the maximum emission occurs at the same place for both gases, seemed to prove the point. The present data furnish further evidence that the cause is due to dissociation. For, using a graphite arc on 4 amperes, when the arc is short, and the hottest, the maximum occurs at 4.65 μ. When the salts of the metals are introduced into the arc they are ionized and the metals carry the greater part of the current. The resistance is reduced, and hence the temperature (and dissociation of CO_2) is reduced. Here the maximum is at a shorter wave-length corresponding to less dissociation of CO_2. While this explains certain points it fails to account for the lack of an emission band when the current is large, 8 to 15 amperes. It is hardly permissible to assume that neither CO or CO_2 is formed at this high temperature and that the electrode disappears in the form of vapor, though the writer made this assumption at the conclusion of his previous examination of the carbon arc.

The change in density of the gases in the two cases will not account for the observations, for even the smallest amount of CO and CO_2 is capable of emitting perceptible radiation, as was found in the experiments with the vacuum tube. As a whole, the mechanism producing this radiation is not understood and further experiments will be needed to gain insight into this subject.

THE INVESTIGATIONS OF MOLL.

While the above experiments on the carbon arc were being concluded the investigations of Moll[1] on infra-red metallic spectra appeared in print. He examined the emission spectra of the salts of the metals of Na, K, Rb, and Cs in the carbon arc, using for the purpose a rock-salt prism, a thermopile, and an automatic device for recording the galvanometer deflections. The apparatus was a little more sensitive than the radiometer previously used by the writer, while his dispersion was almost twice as great, and with the automatic device he was able to explore the region beyond 2 μ more thoroughly than was possible by making personal observations. In

[1] Moll: Onderzoek van Ultra-Roode Spectra, by W. J. H. Moll. Dissertation, Utrecht, 1907; Proc. Amsterdam Acad., Feb. 21, 1907.

the region from 2 to 4 μ he succeeded in resolving the emission into separate bands, which the writer, from the smallness of the deflections and the limited number of observations, recorded as a continuous spectrum. He found the CO_2 band at 4.44 μ when he used the salts in the arc, and also for various kinds of carbon electrodes. His energy curves for sodium and for potassium are given in figs. 53 and 54, respectively, in which the resolution of the energy in the region of 1.5 to 4 μ into separate bands is well illustrated. The automatic apparatus succeeded in doing what physical

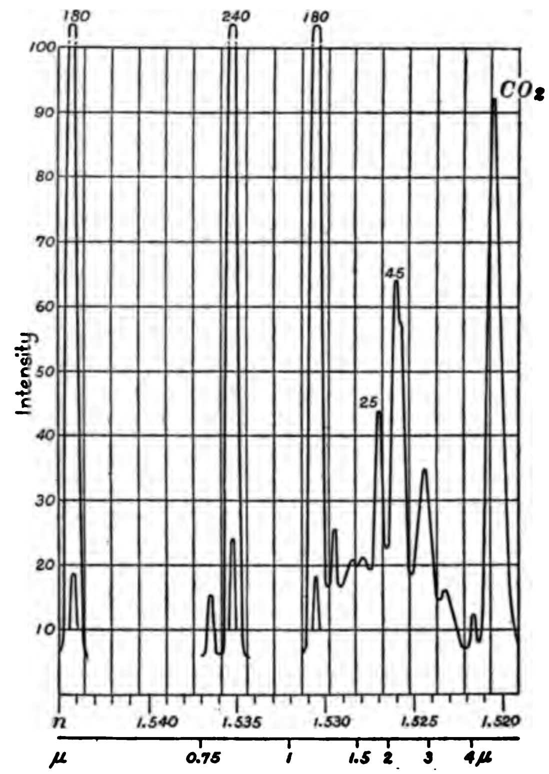


FIG. 53. — Emission of sodium (Moll).

endurance would hardly permit, in mapping this region. No curves are published for the carbon electrodes, but considerable comment is made on the fact that in every case he observed an emission band of CO_2, while the present writer did not find the band, except when using salts in the arc. From the aforesaid observations on the radiation from graphite, it is evident that the conditions were different in the two cases. The writer had observed the same phenomena as did Moll, who, in his comments, missed the point emphasized by me, viz, that whether or not the spectrum at 2 to 4 μ is a complex of small emission bands, the emission bands of the alkali metals at 0.76 to 1 μ are the most intense in the whole spec-

trum, indicating a much higher temperature (if the radiation is purely thermal) than would be the case if the emission bands at 2 to 4 μ were the more intense.

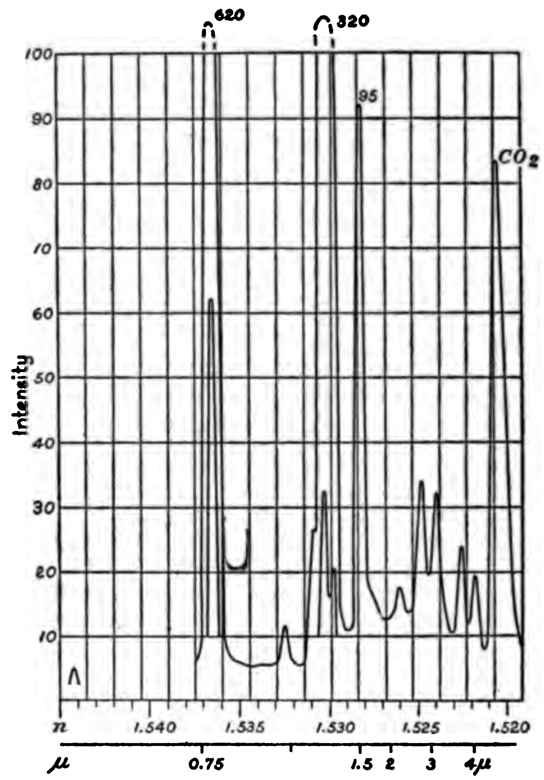


FIG. 54. — Emission of potassium (Moll).

RADIATION AT ROOM TEMPERATURE.

The distribution of energy in the spectrum of a complete radiator has been determined for temperatures varying from 373° to 1800° abs., and the constant in the "displacement law" $\lambda_{max}\ T=A$ has been found to be 2930 (2940, Lummer and Pringsheim; 2920, Paschen). For bright platinum the value of this constant is about 2630. The measurements of Lummer and Kurlbaum[1] show that at low temperatures (492° abs.) the emissivity of iron oxide is 0.3, while bright platinum is only about 0.04 that of a complete radiator at the same temperature. The spectral distribution of radiation at low temperatures has been given but little attention. This is due in part to the impracticability of reducing the temperature of the radiation meter below that of the room. The problem is therefore reversed, in that the radiation meter (bolometer, radiometer, or thermopile)

[1] Lummer & Kurlbaum: Verb. Phys. Ges. Berlin, 17, p. 110, 1898.

is allowed to radiate to what is generally the source, which is at a much lower temperature. The first examination was made by Langley:[1]

He located the maximum galvanometer deflection in the region of 8 μ, but adds that the position of "the maximum depends upon a single observation of some delicacy, which is liable to subsequent correction." He further adds that for this temperature difference of $-18°$ the maximum ought to be at 10 to 11 μ. This would indicate that there was some confusion of ideas as to what was really taking place. The energy emitted by the vessel of ice and salt is very small in comparison to the amount it absorbed from the bolometer. Hence the galvanometer deflections are a measure of the radiation emitted by the bolometer to the vessel of snow and ice, and the observed maximum is for a temperature of $-2°$ instead of $-18°$ C. However, since a bolometer strip is always at a higher temperature than the surrounding atmosphere, it is quite probable that, although the observations were made during zero weather, the maximum observed is really due to a higher temperature of the source (bolometer strip) than $-2°$ C. In fact, from the "displacement law," which was then unknown, and from our present knowledge of radiation of different surfaces, it is quite possible that the temperature of the bolometer was as high as 20 to 30° C.

Mendenhall and Saunders[2] state that they found the energy curve of a complete radiator at $-90°$ C. From their discussion of the energy curve of a body at the temperature of boiling liquid air where the emission maximum should lie at 30 μ (which, of course, is possible if one could reduce the temperature of the radiometer below this point in order to make measurements), it would appear that they, too, had not considered their radiation curve to be due to the bolometer strip. Moreover, the use of a bolometer to deduce a distribution of energy curve at low temperatures, where the bolometer itself becomes the source, is not very satisfactory, due to the fact that the temperature of the radiating strip can not be determined.

Lummer and Pringsheim[3] obtained a small portion of the spectrum energy curve of a screen at room temperature, which they used during their radiation experiments. The first really lucid discussion of the subject is due to Stewart,[4] who found the spectrum energy curve of a Nichols radiometer radiating to a receiver at liquid-air temperature. The maximum deflections observed were 4 mm. The temperature of the room (and radiometer vane) was 24° C. or 297° abs. The observed maximum

---

[1] Langley: Amer. Jour. Sci., 31, p. 1, 1886. "The radiator was the bolometer itself at a temperature of $-2°$ C., and the source radiated to was a vessel of snow and salt at $-20°$ C., thus determining the distribution of energy in the spectrum of a surface below the freezing-point of water."

[2] Mendenhall & Saunders: Astrophys. Jour., 13, p. 25, 1901.

[3] Lummer & Pringsheim: Verb. Phys. Ges., 2, p. 163, 1900.

[4] Stewart: Phys. Rev., 17, p. 476, 1903. (In this paper figs. 4 and 6 are interchanged.)

of his energy curve, corrected for slit-width, occurs at 9.2 μ, while the value computed from the "displacement law," using the temperature 297° abs. and $A=2920$, would be found at 9.8 μ. If we compute the value of this constant from the observed values of λ_{max} and T, then $A=2722$, which is about 6 per cent lower than for a complete radiator. From experiments on the radiation from plane surfaces, such as a radiometer vane, this departure from the radiation of a full radiator is to be expected. Then, too, this form of radiation is complicated by the window before the radiometer vane. In general, the intervening material between the source and the receiver would have no effect. For very delicate radiometers, however, the writer found (Carnegie Publication No. 35) that the inequality in the radiation from the radiometer window had a great effect upon the position of the vanes. Just how much this would affect the vane in the present case is unknown. In the present investigation a Rubens thermopile (20 junctions of iron-constantan) was allowed to radiate to a copper vessel at liquid-air temperature. A mirror spectrometer and rock-salt prism, described in Carnegie Publication No. 65, were employed to produce the energy spectrum. The only changes introduced consisted in replacing the Nernst heater by a short focus mirror, which projected an image of the bottom of the vessel at liquid-air temperature, upon the spectrometer slit. The galvanometer used with the thermopile had a sensitiveness of $i=2\times10^{-10}$ amperes and a full period of about 12 seconds. The deflections were very unsteady, due to air currents caused by the evaporation of liquid air. The thermopile was placed in the position formerly occupied by the radiometer and was covered by the inner metal shield, with a slit 1 by 15 mm. area. The whole was inclosed in a metal tube covered with felt.

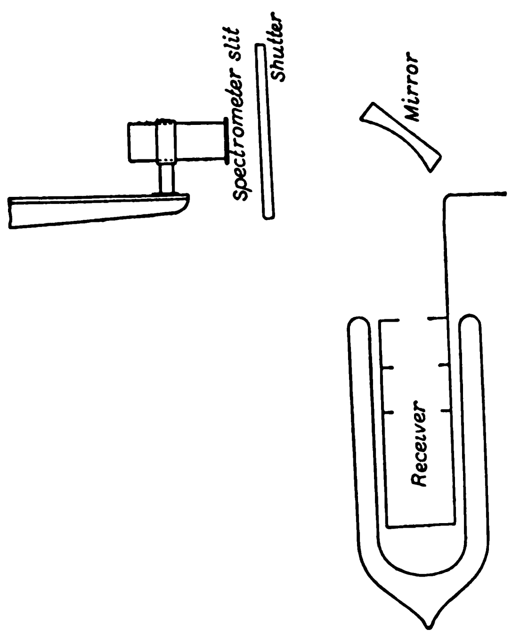


FIG. 55.

This formed a more perfect black body than is possible with a radiometer. The receiver to which the thermopile radiated consisted of a thin cylindrical copper vessel about 4 cm. diameter and 12 cm. long (covered on the inside with copper oxide and lampblack), which was suspended in a vessel of liquid air, as shown in fig. 55. The receiver was kept stationary and

the height of the vessel of liquid air was regulated. The temperature changed so rapidly that it was necessary to begin taking readings with the liquid air just touching the bottom of the vessel, when fairly consistent results were obtained. The observations are plotted in fig. 56. Curve *a* is plotted through the mean values of the observations, while curve *b* is drawn through the highest observed values. The two curves are fairly consistent, considering the difficulties in making the observations. In the region of 6 μ atmospheric absorption reduced the deflections.

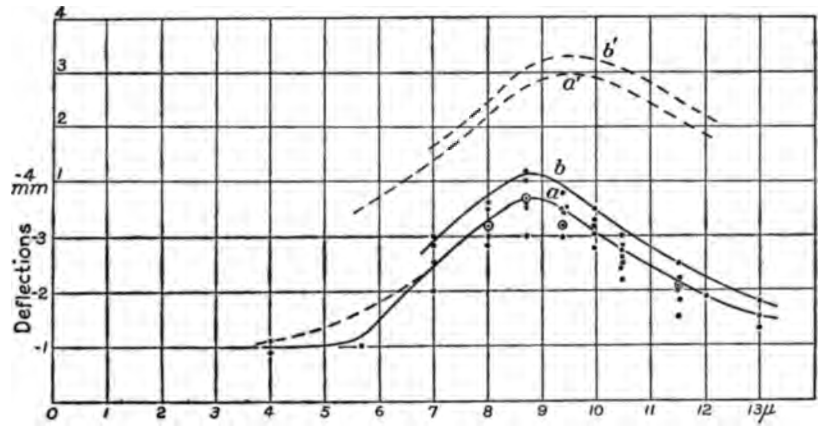


FIG. 56. — Emission spectrum of Rubens thermopile.

Curves a' and b' are the two lower curves after correcting for variation in slit-width, *i.e.*, reducing them to a normal spectrum. The maximum of these radiation curves lies at about 9.6 μ. The temperature of the thermopile was 21° C., or 294° abs. Substituting these values in the "displacement" formula, the constant is $A = 2822$, which is about 3 per cent smaller than that of a complete radiator. For the latter, the maximum would occur at about 9.95 μ. It appears that the thermopile approaches very closely to that of a Kirchhoff radiator.

SELECTIVE RADIATION FROM THE NERNST GLOWER.[1]

The study of the radiation from metal filaments of incandescent lamps is of interest in connection with the speculations as to whether the great light emissivity (high luminous efficiency) is due to an abnormal emission in the visible spectrum, with a corresponding suppression of the radiation in the infra-red, or whether the effect is due to the high temperature at which the lamp is burning. In the latter case, the distribution of energy in the spectrum may be uniform (no discontinuities), but a great deal of it will lie in the visible spectrum. From a theoretical consideration[2] of

[1] A detailed description of this investigation is given in the Bulletin of the Bureau of Standards, vol. 4, p. 533, 1908.

[2] Aschkinass, Ann. der Phys. (4), 17, p. 960, 1905; Einstein, Ann. der Phys. (4), 17, p. 132, 1905; 22, pp. 191, 569, 800, 1907.

the fact, that the filaments are metallic, electrical conductors with a high reflecting power in the visible, and probably reflect uniformly high in the infra-red, one would expect the distribution of energy in the spectrum to follow a law similar to that of platinum, but with different constants. The results thus far obtained from a study of such metals as tungsten and osmium support this hypothesis. On the other hand, in the case of oxides, which conduct electrolytically at high temperatures, there is no data to form even a working hypothesis. All the oxides thus far examined have no strong absorption bands near the visible spectrum; the only exception being the oxides of the rare earths, such as cerium, thorium, lanthanum, didymium, erbium, etc., the compounds of which have strong, sharply defined absorption bands in the visible, and at least some of these have absorption bands in the infra-red. It seems to be a characteristic of the oxides, that they have a low reflecting power (like transparent media, electrical non-conductors) throughout the infra-red to about $8\,\mu$ beyond which point they have strong bands of metallic reflection. In this region of metallic reflection, the emission will be suppressed[1] in proportion to the reflecting power. In the rest of the spectrum, the emission will be proportional to the absorbing power (general absorption), while at the point where there is a band of selective absorption in the transmission spectrum, there will be an emission band in the emission spectrum, provided the radiation is a purely thermal one, following Kirchhoff's Law.

In the case of the Auer mantle the emission spectrum[2] is a series of emission bands at 1 to $2\,\mu$, with practically no emission in the region from 4 to $7\,\mu$, while beyond $9\,\mu$ the spectrum is continuous, and is apparently as intense as that of a complete radiator at the same temperature.

In the case of the Nernst glower, which is a combination of the oxides of cerium, thorium, and zirconium, belonging to the "rare earths," the compounds of which are noted for their strong absorption bands, one would expect the emission spectrum to show strong, sharp emission bands; at least one would hardly expect the emission to follow the same general law of spectrum energy distribution as is known for metals. This, however, has been done in the past, notably by Lummer and Pringsheim,[3] and by Mendenhall and Ingersoll.[4]

The first two investigators, from a rather cursory examination of the Nernst filament, under normal power consumption, found a smooth continuous curve, with a maximum at wave-length $\lambda_{max}=1.2\,\mu$. From this and from the Wien displacement law, $\lambda_{max}\,T=$const. (const.$=2940$ for "black body,"$=2630$ for platinum), assuming that the Nernst glower

[1] Aschkinass, Verh. J. Phys. Ges., **17**, p. 101, 1898. Rosenthal, Ann. der Phys. (3), **68**, p. 791, 1899.

[2] Rubens: Phys. Zeit., **6**, p. 790, 1905.

[3] Lummer & Pringsheim: Verh. Deutsch. Phys. Gesell., **3**, p. 36, 1901.

[4] Mendenhall & Ingersoll: Phys. Rev., **24**, p. 230, 1907; **25**, p. 1, 1907.

belongs to the same class of radiators as platinum and a "black body," they computed $\lambda_{max} = 2450°$ abs., and $\lambda_{min} = 2200°$ abs.

Their computed energy curve of a "black body" having its maximum emission at 1.2 μ departs considerably from the observed curve. Mendenhall and Ingersoll compared the emission of the Nernst glower in terms of a constant comparison lamp, at a certain wave-length in the visible spectrum, at the melting points of gold and of platinum. From this they extrapolated on a straight line assuming that Wien's equation holds for the glower, and found the temperature at normal or any desired power consumption. This leads to erroneous values (which are probably too high, as will be shown presently), due to the fact that the spectrum is the composite of numerous emission bands, which rapidly increase in intensity, in the short wave-lengths, with rise in temperature. They found the normal temperature to be 2300° abs., disagreeing with a recent determination by Hartman,[1] who, by means of thermocouples of different thickness placed against the glower, correcting for heat conduction by extrapolating to a temperature corresponding to an infinitely thin couple, found the temperature to be 1800 abs. Although this method had previously been extensively used, with fair success, in measuring temperature of gas-flames, it is not suited to the glower, in which there is no layer of hot gas to even partially compensate for the heat lost by conduction.

That the Nernst glower emits selectively in the visible spectrum, has been shown by Kurlbaum and Schulze,[2] who found a minimum of emission at 0.52 μ, which became fainter with rise in temperature, and disappeared entirely at high temperatures.

To this brief review of what has been done on the Nernst glower may be added a paper by its inventor,[3] who showed that the conductivity is electrolytic, while Kaufmann[4] showed that in spite of the entirely different inner mechanism of conduction of a gas in a vacuum-tube, and in a Nernst glower, the electrodynamic phenomena are nevertheless very similar.

The present investigation of the Nernst glower consists in mapping the distribution of energy in the spectrum, varying the power consumption, and hence the temperature.

The apparatus used in this work consisted of the mirror spectrometer,[5] used in the preceding experiments, a perfectly clear fluorite prism, having an angle of 60° and circular faces 33 mm. in diameter, and a bolometer[6] with a hemispherical reflecting mirror. The bolometer strip and spectrometer slit were 0.6 mm. wide, or about 4′ of arc. The upper part of the

---

[1] Hartman: Phys. Rev., 17, p. 65, 1903.

[2] Kurlbaum & Schulze: Verh. Phys. Gesell., 5, p. 428, 1903.

[3] Nernst: Zeit. für Electrochemie. 6, p. 41, 1899.

[4] Kaufmann: Ann. der Phys. (4), 2, p. 158, 1900; 5, p. 757, 1901.

[5] For adjustments see "Investigations of Infra-red Spectra," Carnegie Institution of Washington Publication No. 35, 1905.

[6] Described in this volume, Appendix II.

spectrometer, containing the collimating mirrors, and the Wadsworth mirror-prism outfit, were entirely inclosed by a thin sheet-metal box, lined with black velvet. The spectrometer slit was covered with a clear plate of fluorite. The openings in the top, for adjusting the mirrors, were closed with soft wax, while the hole admitting the axis for rotating the mirror-prism table was tightened with a nut and packing.

Within the box, and below the level of the mirrors, were placed vessels containing phosphorous pentoxide and sticks of potassium hydroxide, which entirely eliminated the absorption bands of CO_2, and water-vapor from the emission curves. A water-cooled shutter was placed before the spectrometer slit, and the Nernst glower, inclosed in an asbestos case to prevent air-currents, was placed close to the shutter. Observations were also made without inclosing the glower, to prove that the effects observed are not due to stray radiation from the asbestos case. In spite of all that has been written about bolometers, it may be added that there was no "drift," unless a poor storage battery was accidentally used.

The auxiliary galvanometer of 5.3 ohms resistance, with a single swing of 4 to 5 seconds, had a current sensibility of $i=1.6$ to 1.5×10^{-10} ampere. A greater sensitiveness for the same period would have been possible, by using a lighter suspension. The present suspension of ten needles was just heavy enough so as not to be affected by tremors.

Using a battery current of 0.04 ampere the computed temperature sensibility was $5^{\circ}\times10^{-6}$ C., which was generally far in excess of that required. The deflections were reduced to 14 to 15 cm., by inserting resistance in series with the galvanometer. The individual readings would vary by 1 mm. or less than 1 per cent, which is as close as the nature of the work required, since the actual deflections were as high as 2000 cm. Furthermore, at high temperatures (especially when operated above normal power consumption) the filament would deteriorate in emission by that amount during the series of observations.

The calibration curve of the fluorite prism was constructed from the refractive indices, found by Paschen,[1] which, after plotting all the observations made by different observers, seems to be as close to the most probable values as observations will permit. Unfortunately the dispersion curve passes through a double curvature at $1.5\,\mu$, just where the energy spectra have their maximum. In the region of $1.5\,\mu$, the correction for purity, so-called "slit-width" correction, is a maximum.

The wave-lengths in the calibration curve were plotted to the fourth decimal place, so that there is a certainty of the values to at least the second decimal place. This, however, is of less importance than the value of the slit-width correction, which was made according to Paschen,[2] the values being obtained from a curve plotted on a large scale to insure

[1] Paschen: Ann. der Phys. (4), 4, p. 299, 1901.

[2] Paschen: Ann. der Phys. (3), 60, p. 714, 1897.

an accuracy greater than required in the work. In a few cases a correction was made for the reflecting power of the silver mirrors, but it was found negligible except in the visible spectrum.

With this apparatus, a series of energy curves was obtained, varying the power-consumption from 16 watts (the lowest at which the glower would conduct on 110 volts) to 123 watts, which is far above the normal. The energy curves, which were continuous, underwent great variations in appearance with rise in temperature. At 2.5 and 3.5 μ depressions would generally appear in the curves, which could not be attributed to experimental errors, and since previous work by others seemed to show that the spectrum is continuous, an attempt was made to locate the disagreement in the apparatus (in the calibration, or in the slit-width correction curve), but nothing would account for it until the filament was run on a 2000-volt transformer which permitted the heating of the glower at a very low power-consumption. At the lowest temperature the glower was a grayish red. The results are given in fig. 57 (110-volt A. C. glower No. 118), and are entirely different from anything hitherto recorded in the emission of solids in the infra-red. At the lowest temperatures (800° to 900° C.) the bands in the region of long wave-lengths are the most intense. As the temperature increases, the bands in the region of 2.5 μ increase very rapidly in intensity, so that by the time the temperature has increased to 1000 to 1100° the intensity of the group of bands at 2 μ is far in excess of those at 5.5 μ.

The depression at 3 to 3.5 μ is to be noticed, for it persists even at normal power-consumption. The region at 2.5 μ is also to be noticed, for the curves at higher temperatures often show a slight depression, not attributable to experimental errors. As the temperature rises (curve *e*, fig. 57) new emission bands appear, notably at 2.5 and 4 μ. This shift of the maximum of intensity of the bands, with increase in temperature, is to be expected, if the emission is a purely thermal one, following Kirchhoff's law, and is the most conspicuous illustration yet recorded.

In fig. 58 are given the emission curves for the glower (200 volts, serial No. 118) at 19.6 and 102.5 watts, respectively. It is to be noticed that the emission curve has already become smooth and continuous, with but two maxima, at 1.4 and 5.5 μ, respectively. In this figure curve *b* is one-tenth the scale of curve *a*.

On the whole, from whatever point of view we consider the data at hand, it is evident that even after the emission spectrum has become apparently continuous it does not follow so simple a law as has been established for solids emitting continuous spectra. It is also evident that any estimation of the temperature of the glower based on these laws will lead to erroneous results. From a commercial point of view the efficiency of such a radiator, in which the emissivity is abnormally high at 0.6 to 0.7 μ, while the maximum at 1.2 μ is abnormally low, must be much higher than that of some

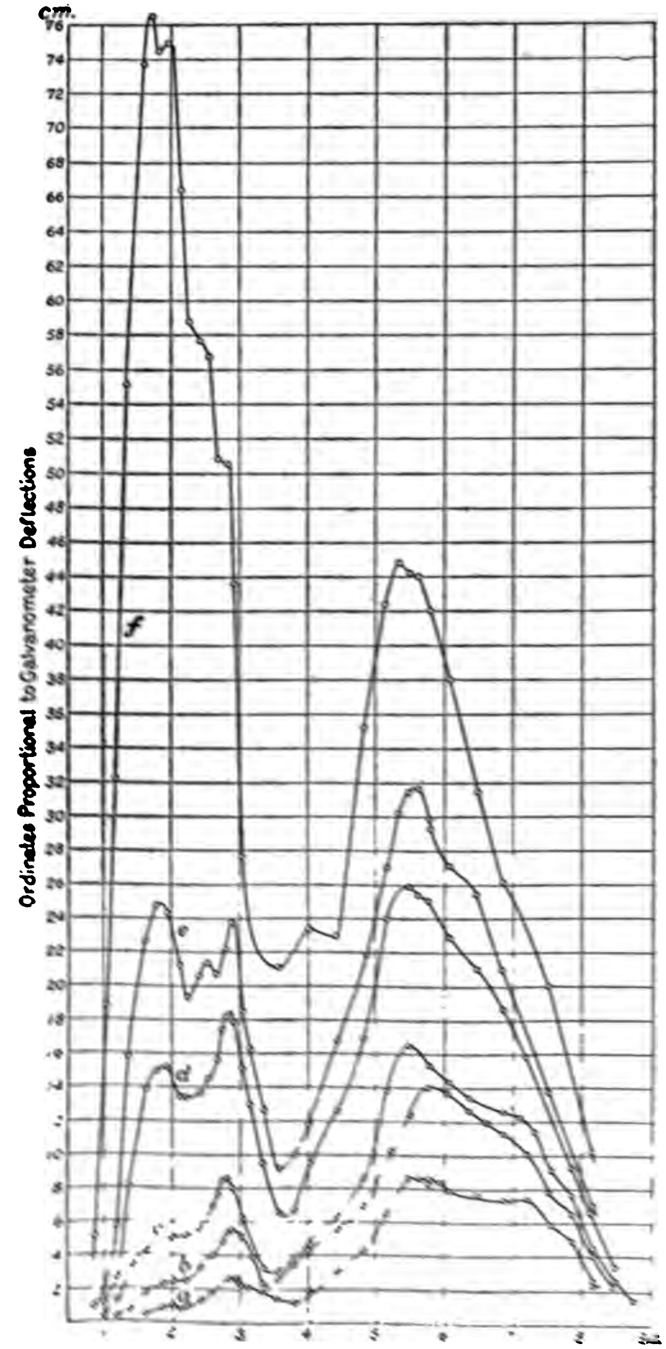


FIG. [illegible]. — Emission spectrum of Nernst glower. a = [illegible], b = [illegible], c = [illegible], d = [illegible], e = [illegible], and f = [illegible] watts, respectively.

substance having a radiation law similar to platinum, in which case, in order to attain a similar intensity in the visible, the maximum at 1.2 μ rises to extremely high values.

The results obtained are for filaments made from different lots of material, the 220-volt glower being at least 5 years old. The observations have been made at different dates, on different filaments, all in duplicate, some quadruplicate, and there is reason for feeling that what has

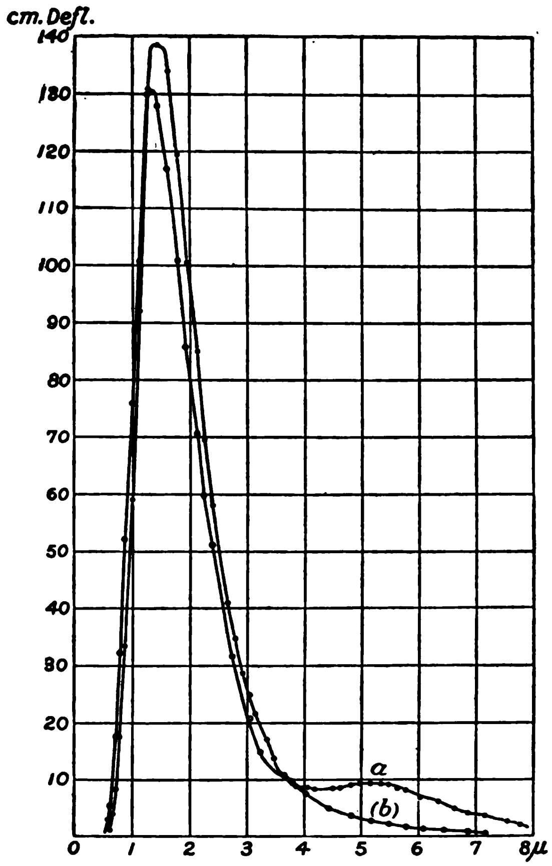


FIG. 58. — Emission spectrum of Nernst glower; (a) = 19.6 watts, (b) = 102.5 watts; λ_{max} = 1.45 μ and 1.32 μ, respectively.

been observed is a reality. No doubt on examination of other makes of filaments, there will be found a variation in the finer details of the emission bands, at low temperatures, but the gross results can hardly be modified without employing a much larger dispersion and a much narrower bolometer. Some of these bands coincide with certain ones found in the emission spectrum of the Nernst "heater," the results of which are given in Carnegie Publication No. 35.

RADIATION FROM METAL FILAMENTS.

The measurement of very high temperatures is based upon an extrapolation of the laws governing the energy emitted by a body with change in temperature. Our knowledge of these laws is confined to the radiation from platinum and from a uniformly heated cavity (so-called black body) which is the nearest approach to a complete radiator. The remarkable progress made in the development of processes requiring an accurate knowledge of the temperatures involved makes it imperative to study the laws of radiation of various substances with variation in temperature. The object of this and of subsequent investigations is to gain an insight into these laws. In order to determine these radiation laws it is generally necessary to study the spectrum energy curves, using for the purpose a prism that is transparent to heat rays, and some sort of very sensitive heat-measuring device, such as, for example, a bolometer or a thermopile. It is also possible to study the total radiation emitted. The chief difficulty in studying these so-called radiation constants of substances lies in the impossibility of determining the temperature of the radiating surface.

The curves showing the distribution of energy in the normal spectrum of all solid bodies thus far studied are unsymmetrical with respect to the maximum, having the appearance of the probability function, modified by suitable constants. The solids heretofore studied, *e.g.*, platinum, in which it was possible to determine the approximate temperature, have spectrum energy curves, which are represented fairly well by the function,

(1) $$E = c_1\lambda^{-\alpha}e^{-c_2/\lambda T}$$

In the case of a complete radiator,[1] or so-called "black body," the exponent $\alpha = 5$, while for platinum, $\alpha =$ [illegible].

In order to determine the constants of the above equation from the spectrum energy curves, it is necessary to know the temperature of the radiator. Fortunately the index α may also be obtained from the spectrum energy curve in which the temperature T is constant (E = galvanometer deflections, λ = wave length, are variable), without knowing the actual temperature, for it can be shown from equation (1) that the ratio of the emissivities (the observed bolometer galvanometer deflections) for any two wave lengths, λ and λ_{max}, is:

(2) [illegible]

from which the value of α may be obtained. It was found by Paschen

[1] [illegible]

that for carbon, platinum, etc., the value of a was in agreement with that obtained from a knowledge of the temperature of the radiator.

With this equation it is possible to obtain some idea of the probable total emissivity of a radiating body, as to whether it is proportional to the 4th power ($a-1=4$ for a black body, $a-1=5$ for platinum), or to some higher power of the absolute temperature. Of course the assumption is made that the emissivity function is similar to that of platinum and of a black body. The appearance of the energy curves for various temperatures will give some clue as to the admissibility of this assumption, which is nothing more than has been made by previous observers. How far this assumption falls short of the observed facts, may be seen in figs. 57 and 58 for the Nernst glower, which has a spectrum composed of numerous emission bands. With substances whose energy spectra undergo no change in contour with change in temperature, it does not seem unreasonable to apply our knowledge gained from the behavior of platinum under similar conditions, especially since the filaments are metals, electrical conductors, which, theoretically,[1] should have similar emissive properties. That the

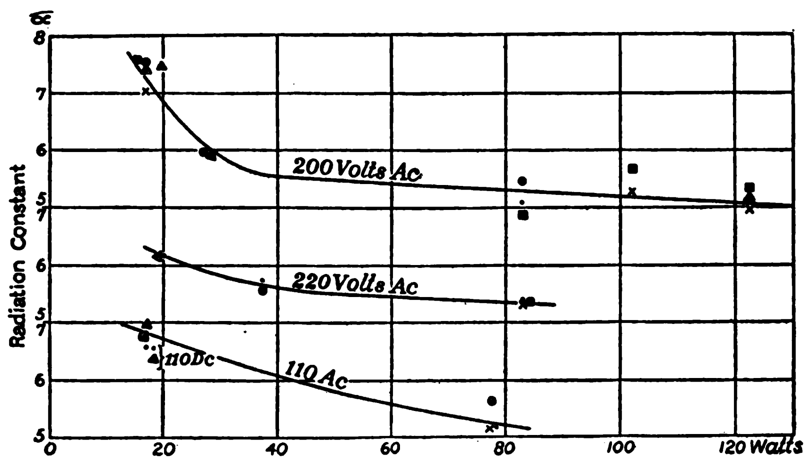


FIG. 59. — Radiation constant (a) of Nernst glower.

method is open to criticism is admitted, but until a better one is suggested, the present method is the only one available without a knowledge of the temperature of the radiator. The apparatus used in this work consisted of a mirror spectrometer, a fluorite prism, and a bolometer, mentioned in the description of the results on the Nernst glower.

The variation of the radiation constant a for the Nernst glower with rise in temperature is shown in fig. 59, from which it will be seen that it decreases from a value of 7 at 18 watts to 5.3 at 80 to 120 watts. These values are taken from the smooth energy curves, such as those shown in

[1] Aschkinass: Ann. der Phys. (4), 17, p. 960, 1905. Einstein: Ann. der Phys. (4), 17, p. 132, 1905; 22, pp. 191, 569, 800, 1907.

fig. 58. The curve for 102 watts was irregular in outline and the values of a obtained at different wave-lengths (indicated by crosses, circles, dots, squares, etc.) undergo great variations. On the whole, it is evident that it is hardly permissible to obtain this constant on the assumption that the radiation law of the Nernst glower is similar to that of platinum or of a complete radiator. The energy curve of a complete radiator having a maximum emission at 1.45 μ falls far below the Nernst glower curve (a, fig. 58) at 5.5 μ, which shows that the emission at 1.45 μ is not as intense as it should be if the emissivity were similar to a complete radiator. For the same reason, the spectral energy curve of a complete radiator having a maximum at 1.32 μ lies far above the glower curve (b, fig. 58) at 5.5 μ.

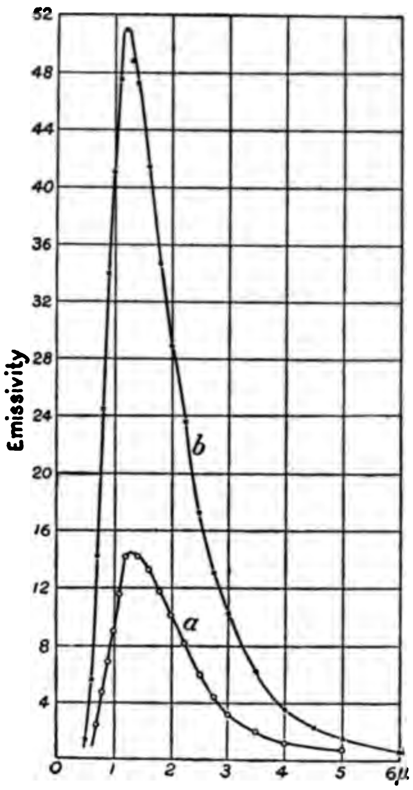


Fig. 60. — Radiation from osmium.

In fig. 60 is shown a series of energy curves of an incandescent filament (3 cm. long) of osmium, when on an energy consumption of curve $a=2.44$ and curve $b=7.38$ watts, respectively. The corresponding temperatures, observed with an optical pyrometer, using red absorption glass, are 1607° and 2000° $K._{.66\lambda}$ C., respectively, while the computed temperatures, on the assumption that the radiation constants are the same as for platinum (for $\lambda = 1.35$ and $1.2\ \mu$), are 1670° C. and 1907° C., respectively.

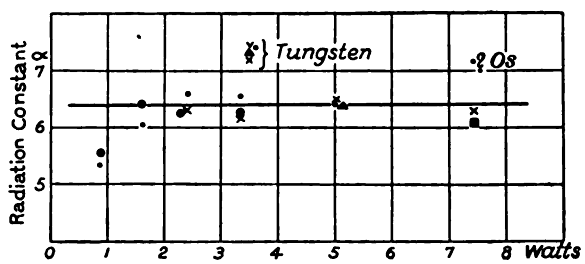


Fig. 61. — Radiation constant (a) of osmium.

These filaments were in glass bulbs similar to that of an incandescent lamp, and had short side tubes with fluorite windows. Fig. 61 shows the value of a of osmium (of fig. 60) for variation in energy consumption.

Except for the lowest temperatures the value of a obtained by this method is about 6.4. The surface became roughened, which lowers the value of this "constant." The weakness of this method lies in the difficulty of obtaining the values of the emissivities, particularly the maximum of the energy curve. Since the filaments are so narrow that the prism-face is only partly covered, the height of the ordinates will depend upon the cone of energy falling upon the prism face. For this reason the energy curves of the different substances can not be compared. The value of a for a short tungsten filament (see fig. 61) was found to be 7.3 for one energy curve. Further experiments on another filament gave a value of $a = 6.88$ for the mean of 18 computations and 5 energy curves. The values of a for an untreated carbon filament, for various values of energy consumption, are plotted in fig. 62. As with osmium, the temperature was raised from a

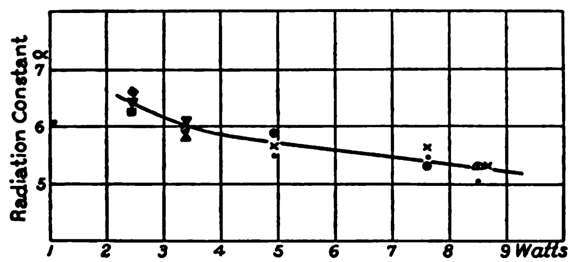


FIG. 62. — Radiation constant (a) of untreated carbon filament.

low red to the normal condition. Apparently the emissivity constant, a, drops from 6.4 at about 900° to 5.3 at 1800° to 2000° C. Paschen found no such variation for the specimens of carbon examined. Neither did he find a variation in a for the oxides of copper and of iron. On the other hand, Lummer and Kurlbaum, by measuring the total radiation emitted, found that with rise in temperature the emissivity of these oxides approached that of a complete radiator. This difference may, of course, be possible, just as in the present examination of the Nernst glower the value of which was found to vary, while Mendenhall and Ingersoll,[1] by using a total radiation method of comparison with platinum, could not establish with certainty any variation of a with temperature. An inspection of figs. 58 and 59 shows that this may be possible, especially in the latter where the energy curve appears to have two maxima. For the "Helion" filament, which is a carbon filament upon which is a deposit of silica, the constant $a = 8.3$ when new, and decreases to 6.3 after aging. For tantalum the value of a is 6.5. From the energy curve of the acetylene flame published by Stewart (Phys. Rev. 16, p. 123) the value of a is about 11. A platinum strip, 50 × 1.5 × 0.02 mm. inclosed in a glass bulb with a fluorite window, was also examined. Estimating temperatures from the position

[1] Mendenhall & Ingersoll: Phys. Rev., 25, p. 1, 1907.

of the λ_{max} ($\lambda_{max} T = 2620$) it was found that the "constant" a decreased from $a = 8.5$ at 900° C. to $a = 6.3$ at 1100° C.

Using metal filament lamps (commercial 110-volt) under "normal" working conditions, for metallized carbon $a = 6.1$, for tantalum $a = 6.3$, for tungsten $a = 6.6$, and for osmium $a = 6.9$. In all cases the value of a was found to decrease with rise in temperature.

Theoretically, this variation in a must occur at some stage in the temperature (either an abrupt decrease at some fixed temperature, or a uniform decrease throughout the range), otherwise a temperature would be attainable at which the total radiation is greater than that of a complete radiator at the same temperature.

In the "black body" the reflection is zero. The Nernst glower, as well as the oxides in general, have a very low reflecting power; hence, if the radiating layer is of sufficient thickness, the emissivity of the oxides must be almost as great as that of a "black body," as has just been found for the Nernst glower, at high temperatures. Some oxides, having absorption bands in the visible spectrum, *e. g.*, CeO_2, when in thin layers (Welsbach mantle) and at high temperatures will have a higher luminous efficiency than the same material in thick rods, *e. g.*, the Nernst glower. In the next chapter it will be shown that the greater the electrical conductivity the more continuous will be the emission spectrum of the oxides. Furthermore, mixtures of oxides like mixtures of gases in a vacuum tube have composite emission spectra. This indicates a possible method of analysis of mineral solutions, and it is hoped to make a further examination into this question.

CHAPTER II.

SELECTIVE RADIATION FROM VARIOUS SOLIDS.

INTRODUCTION.

Our knowledge of the emission of radiant energy from various substances with change in temperature is extremely limited, being confined to platinum in the case of metallic electrical conductors, to several gases in vacuum tubes, to water-vapor and carbon dioxide in the Bunsen flame, to carbon, to the oxides of copper and iron, and to the radiation from a uniformly heated cavity or complete radiator. The emission spectra of the Bunsen flame and of gases in vacuum tubes were found to be composed of sharp emission bands superposed upon a weak continuous spectrum. The solids were found to have smooth continuous emission spectra, and it seems to be the general expectation to find (see Kayser's Spectroscopie, vol. 2, pp. 135 and 284, also Rudorf, Jahrb. Radioakt. und Elektronik, 4, 385, 1908) that all solids emit continuous spectra.

To Paschen is due the credit for the first systematic study of the spectral distribution of radiant energy from various solids, and from the Bunsen flame. Subsequent work by others has been but little more than the establishment of the so-called radiation constants to a greater number of significant figures than was possible by Paschen, with the facilities at his disposal. Great credit is due to Lummer and Pringsheim for establishing the limits within which the radiation laws, notably Wien's law, hold. It must be said, however, that Paschen had these limits partly established; but he insisted that the discrepancies between theory and experiment were due to errors of observation. In this brief summary it is not possible to present the subject fully, but after working over the data, one can not help feeling that it is extremely unfortunate that the results of these investigations are beclouded with controversies as to whom belonged the credit for doing or suggesting this, that, or some other thing in connection with the work.

The best proof of Kirchhoff's law of the proportionality of emission and absorption is due to Paschen,[1] who found that the intensity of the emission of the CO_2 band at $4.4\ \mu$, when using a column of gas 7 cm. long, was as great as for a column of gas 33 cm. long. In other words, the intensity of the radiation was as great as that of a complete radiator for the same

[1] Paschen: Ann. der Phys. (3), 53, p. 26, 1894.

wave-length and at the same temperature. Unfortunately the number of radiating substances of which it is possible to determine even an approximate temperature is extremely small. Hence, the work presented on the following pages can not be more than a qualitative proof of Kirchhoff's law of proportionality between emission and absorption. It has numerous applications, however, particularly in studying substances having sharp emission (hence sharp absorption) bands. Numerous substances are given here, of which it has not been practicable to study the absorption spectra. Their emission spectra give us some idea of the nature of their absorption, the only difference being that the emission bands are more intense, due to the greater thickness (and the higher temperature) of the substance examined. Another feature of the results obtained, which is new, is the extreme sharpness of the emission bands. Moreover, the maxima of the emission and absorption bands coincide, although the temperatures at which the two sets of observations were made differ by 800 to 1000° C. The positions of the sharp, well-defined maxima are not affected by change in temperature. This is in marked contrast with the results of Königsberger[1] for the limited region of the visible spectrum, in which he found that for certain selectively absorbing substances the maximum of the absorption band shifts toward the long wave-lengths with rise in temperature, and with the results of Paschen on the emission bands of CO_2 and water-vapor, which shifted with rise in temperature, some toward the long, others toward the short wave-lengths. The data may also prove to be of use in determining whether pleochroism is an inter- or intra-molecular phenomenon. For example, the absorption spectrum of adularia shows a band at 3.2 μ, which in the emission spectrum is shifted to 2.9 μ. The latter band is characteristic of silicates, whether in the emission or absorption spectrum. The present work may be considered an examination of the emission spectra of electrical insulators, or transparent media. The only previous work done on this subject is due to Rubens,[2] who examined the radiation from the Auer mantle, as well as mantles composed of the pure oxides of cerium and of thorium. The difficulty experienced by him was the elimination of the emission spectrum of the hot gases which was superposed upon that of the oxides composing the mantle. Hence, if he had examined a mantle of zirconium oxide he would not have been able to detect an emission band which occurs at 4.3 μ.

The substances used in the present investigation were in the form of solid rods made in an oxy-hydrogen flame or in the form of thick layers of the substance placed upon a heater. The rods were heated by an electric current from the secondary of a 2000-volt (300-watt) transformer. These rods had, of course, to be heated initially with an alcohol or blast lamp until they became conducting, just as is necessary with the Nernst glower.

[1] Königsberger: Ann. der Phys. (4), 4, p. 796, 1901.
[2] Rubens: Phys. Zs., 6, p. 790, 1905.

The resistance placed in the primary circuit of the transformer to regulate the current, and the low capacity of the transformer, acted as a "ballast" to the radiating substances. The rods were provided with platinum terminals, sealed in the ends, and were securely mounted in incandescent lamp sockets. After heating them until they became conducting, they were mounted securely before the spectrometer slit. The substances that could not be melted and formed into rods were made into a paste and spread upon the "heater tube" of a Nernst lamp. The "heater tube" consisted of a hollow porcelain tube about 5 cm. long and 8 mm. diameter covered with a coil of fine platinum wire, and was used in preference to a platinum strip on account of its rigidity and ease in handling. It gave the same results as the same material on a platinum strip. The spectrometer, the fluorite prism, and the bolometer were previously used in examining the Nernst glower. It is important to notice, however, that by inclosing the optical parts of the instrument it was possible to entirely eliminate the atmospheric absorption bands, which had not been done successfully by previous experimenters. The emission curves are, therefore, within experimental errors, an exact portrayal of the distribution of the energy emitted in different parts of the spectrum. Unfortunately it is not possible to determine the temperature of the radiating body, the thickness of which would have to be specified, in many cases. A thermocouple can not be applied on account of the loss of heat by conduction. It is, of course, absurd to attempt to measure temperatures with an optical pyrometer. For example, the rod of oligoclase was a perfectly transparent glass, and emitted no light other than that due to sparking of the platinum terminals, although at a temperature of 1100 to 1200° C. Nevertheless, a substance such as iron oxide would have emitted light when at the same temperature, while both emit strongly in the infra-red. A further example is the rod of topaz, which was an opaque white mass. On withdrawing it from the oxy-hydrogen flame, it was accidentally stroked with the iron forceps, when the parts so stroked emitted a dull red light, due to the greater emissivity of the iron oxide, while the untouched parts retained their usual white color.

Instead of temperatures, the energy consumption is given; also the dimensions of the rods, the lengths being the distances between the platinum terminals. The diameters are in some cases not very accurate, owing to the irregularity of some of the filaments. The voltage was measured with an electrostatic voltmeter, joined to the terminals of the rod. The current was measured with a milliammeter, of a suitable range to insure accuracy.

It is manifestly impossible to have the smoothness of the surface and the thickness of the radiating layer the same for all substances. The distance (about 2 cm.) of the radiator from the slit and the bolometer sensibility will also vary. No attempt has therefore been made to obtain the emission curves of the various substances at the same temperature,

and to plot them to the same scale. The purpose of the present examination is to map the distribution of energy in the various spectra, hoping that at some future time it may be possible to make a more extended study of certain substances which show unusual emission spectra.

RADIATION FROM ELECTRICALLY HEATED SOLIDS.

Prominent among this group are a series of silicates, which have an emission band in common at 2.88 μ (characteristic of SiO_2) which is as

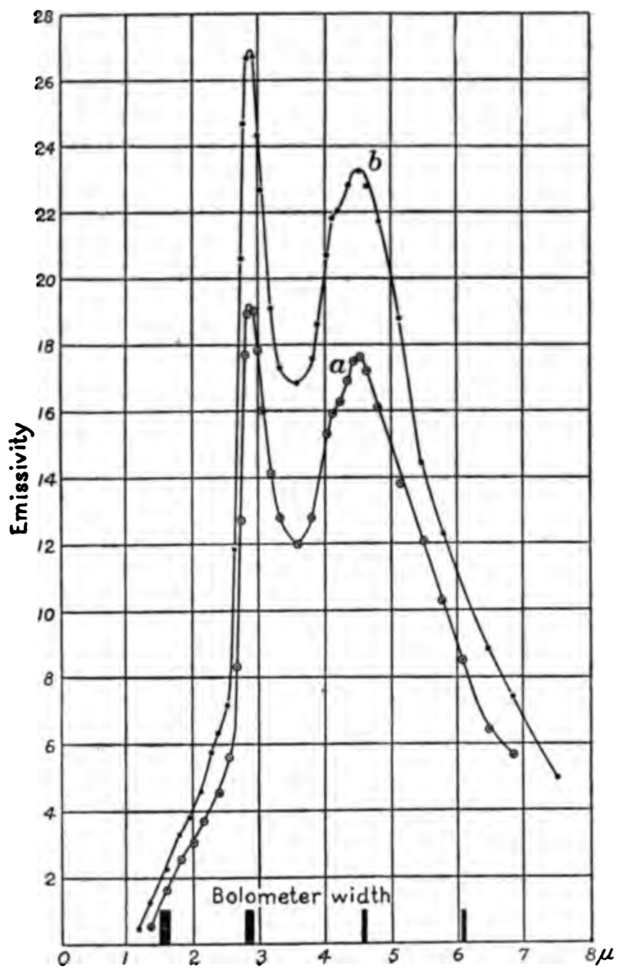


Fig. 63. — Emission spectrum of albite.

sharp as any yet found in gases. The absorption spectra of many of these compounds are recorded in Part III of these investigations (Carnegie Publication No. 65).

In order to give the reader some idea of the conditions under which

the data was obtained, a rough estimate is made of the temperature at which a complete radiator would emit light of a color similar to that given out by the substance under investigation. The fact that soot from the gas flame was burned off the rods not emitting light would indicate that the temperature was above 600° C., and in all cases the estimated temperature is greater than 800° C.

The length of the rods used depended upon the melting-point. For example, the "soft glass" rod was very short on account of its softening at the temperature necessary to keep it electrically conducting. The ends of the rods were shielded from the spectrometer slit. All these curves are reduced to the normal spectrum by dividing the observed galvanometer deflections by the slit-width expressed in wave-lengths. In this work the unsteadiness of the bolometer prevented an accurate mapping of small emission bands occurring beyond 6 μ.

ALBITE ($NaAlSi_3O_8$).

(Rod 8 mm. long, tapering from 1.8 to 2.8 mm. in diameter. Energy supplied, 7.1 and 8.2 watts. Curves *a* and *b*, fig. 63. Temperature 800°. Transmission given in Carnegie Publication No. 65, p. 65.)

The rod was translucent and seemed to emit no light except that reflected from the platinum terminals. The emission band at 2.88 μ is

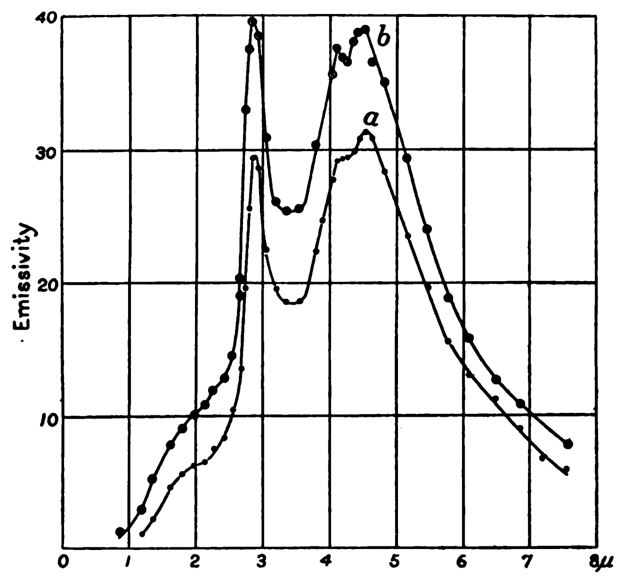


FIG. 64. — Emission spectrum of orthoclase (var. adularia).

more intense than the one found in orthoclase, just as was found in the absorption spectrum. Two other bands are noticeable at 4.1 and 4.5 μ, respectively.

ORTHOCLASE (var. ADULARIA) [$KAlSi_3O_8$].

(Rod 8 mm. long, 2 mm. diameter. Energy supplied, 6.2 and 8.9 watts. Curves *a* and *b*, respectively, of fig. 64. Transmission, Carnegie Publication No. 65, p. 64.)

This substance emitted a little more light than albite, although it was more transparent. The emission band at 2 μ is prominent. The one at

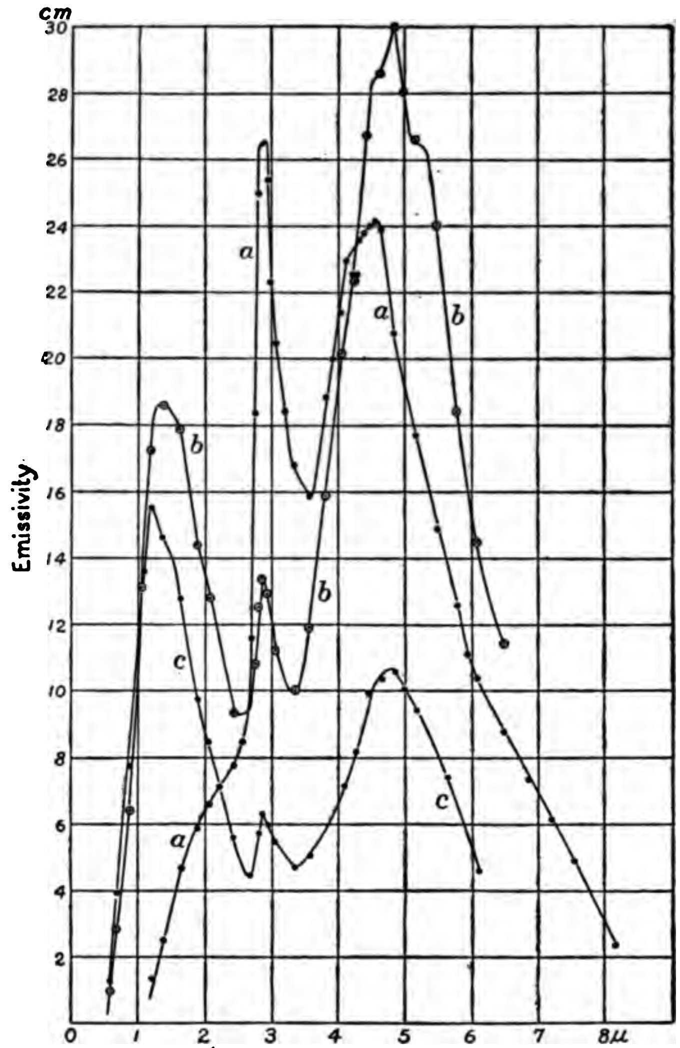


FIG. 65. — Orthoclase (*a*); alumina and silica (*b*); alumina and feldspar.

2.88 μ is shifted from its position at 3.2 μ in the absorption spectrum, from which it would appear that the group of atoms causing the absorption is different in the two cases. An examination of the transmission spectrum using polarized light will be necessary to determine the true

position of the absorption band. The band at 4.1 and 4.5 μ are in common with the other feldspars.

ORTHOCLASE (FELDSPAR) [$KAlSi_3O_8$].

(Rod 7 by 2.2 mm. Energy, 7.5 watts. Curve *a*, fig. 65. Transmission, Carnegie Publication No. 65, p. 64.)

This sample was translucent, due probably to air-bubbles. Its color on 7.5 watts was slightly red, due in part to reflected light from the elec-

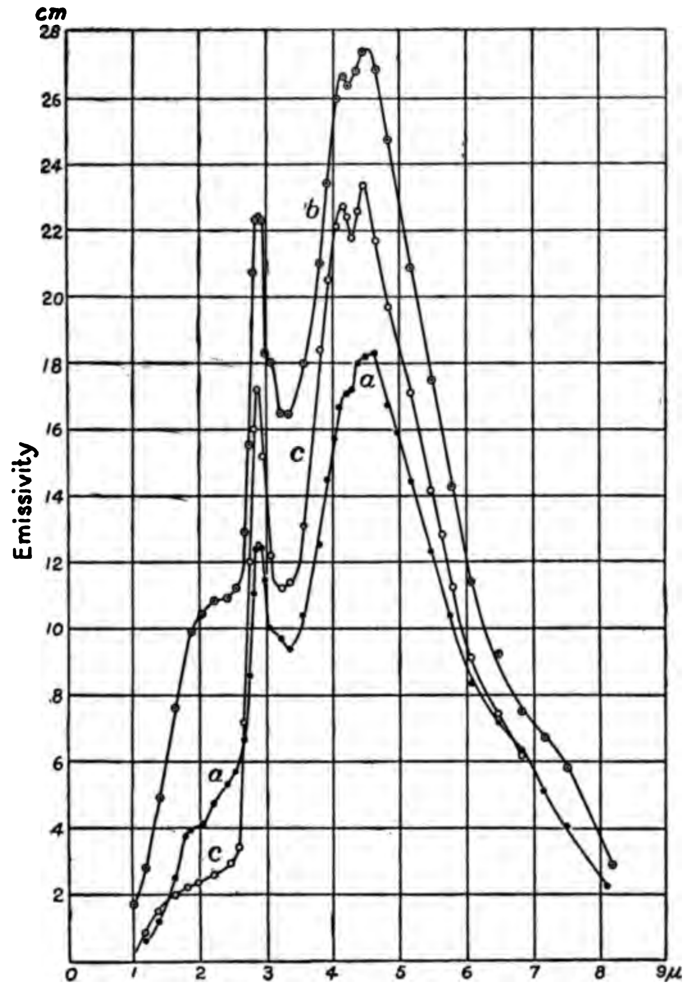


FIG. 66. — Oligoclase.

trodes. The emission bands at 2, 2.88, 4.1, and 4.5 μ are in common with the preceding, with the possibility of a small band at 3.1 μ, to be noticed in fig. 66.

OLIGOCLASE $\left\{ \begin{array}{l} 3\,NaAlSi_3O_8 \\ CaAl_2Si_2O_8 \end{array} \right\}$

(Rod 9 by 2.8 mm. Energy supplied. Curve $a = 8.6$, $b = 13.3$, and $c = 29.4$ watts. Curves a and b, fig. 66. Transmission, Carnegie Publication No. 65, p. 64.)

The original crystal, as well as the glass rod, were perfectly transparent. The rod showed no color on suddenly throwing off the current. The platinum terminals melted on 16 watts, ***but the rod showed no color***. As in the preceding feldspars there are bands at 2, 2.88, 3.1, 4.1, 4.5, and 7 μ. The absorption band at 4.8 μ seems to be shifted to 4.5 μ in the emission spectrum. Curve c shows the distribution of energy when the rod (another sample, plotted to a different scale) was heated until viscous, see fig. 91.

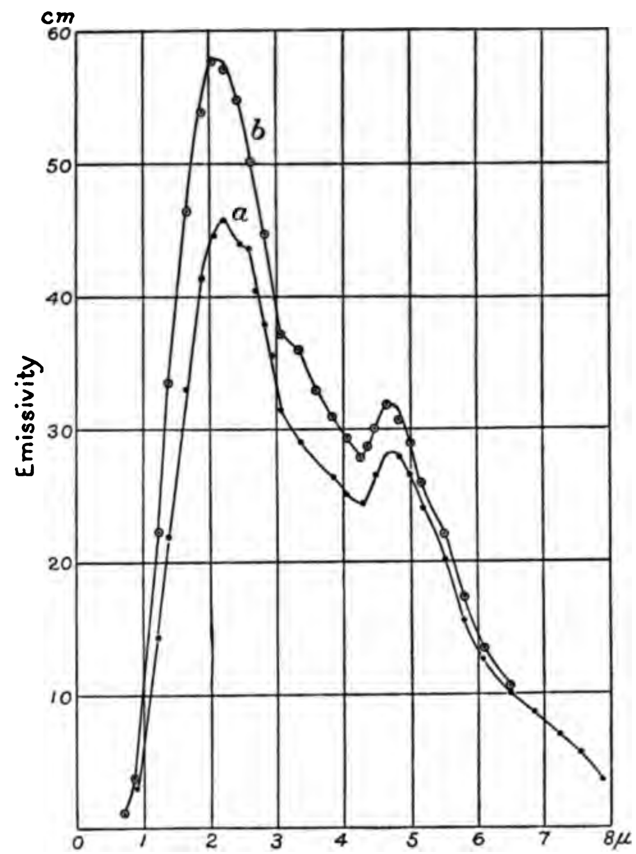


FIG. 67. — Amphibole.

AMPHIBOLE (TREMOLITE?) [$CaMg_3(SiO_3)_4$].

(Rod 6 by 1.5 mm. Energy supplied, 2 (?) and 4.8 watts. Curves a and b, fig. 67. Transmission, Carnegie Publication No. 65, p. 64.)

At the highest energy consumption the color of the filament was a light yellow, corresponding to a temperature of 1200 to 1300°. The emission

curve is quite different from the preceding, due in part to the higher temperature. The absorption band at 6 μ appears as a depression in the emission spectrum.

WOLLASTONITE ($CaSiO_3$).

(Rod 10 mm. long, tapering from 3 to 4 mm. diameter. Energy supplied, 18 watts. Curves *a* and *b*, fig. 68.)

This rod was made from a pure transparent glass, supplied by Dr. Allen of the Geophysical Laboratory of the Carnegie Institution of Washington, which became a white crystalline mass on melting in the oxyhydrogen flame. It was rendered conducting with difficulty, and could not be heated uniformly.

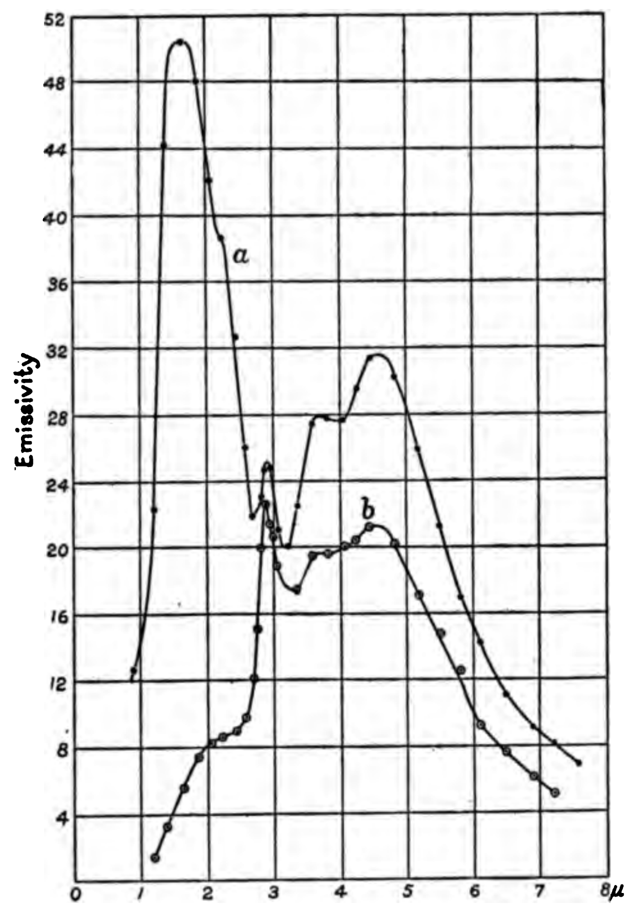


FIG. 68. — Wollastonite.

The silicate band at 2.9 μ is prominent, while a new band appears at 3.7 μ. Curve *b* gives the emission from the coolest side of the rod, while curve *a* represents the emission from the hottest side. The latter is an excellent illustration of the rapid increase in intensity with temperature,

of the emission bands on the side of the spectrum toward the short wave-lengths. Further examples will be found in figs. 77 and 78. In this and in the preceding substance the emission bands are not so sharp as usual, which may be due to the greater molecular weight of the base.

Porcelain (Pyrometer Tubing).

(Hollow rod 15 by 2 mm. (hole 1 mm.). Energy supplied, 9.2 watts. Fig. 69.)

The sample of pyrometer tubing examined was heated to a light-red color (1400°) to keep it conducting. The energy spectrum is marked for

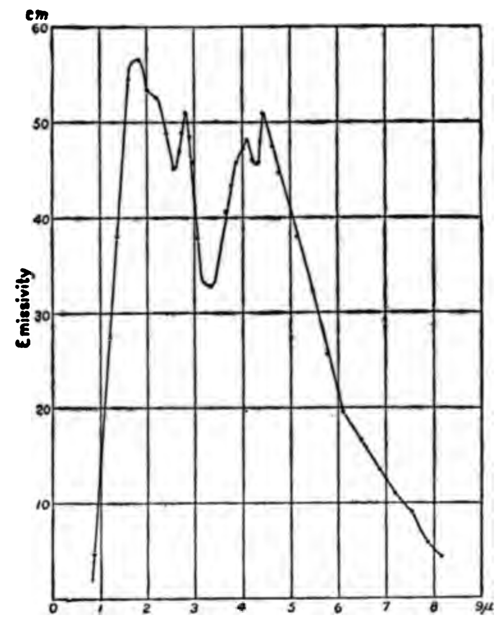


Fig. 69. — Porcelain.

its strong emission, with sharp maxima at 1.8, 2.1, 2.83, 3.7, 4.1, and 4.5 μ, and with indications of bands beyond 6 μ. Porcelain is made from a hydrous aluminum silicate.

Glass ("Soft Glass").

(Rod 3 by 2 mm., heated to dull red color. Curve *a*, fig. 70. Transmission, Carnegie Publication No. 65, p. 65.)

The substance examined was a piece of ordinary "soft" white glass tubing, drawn into a solid rod. There are emission bands at 2, 2.86, 3.6, 4.4, and 5.5 μ.

Magnesia (Pyrometer Tubing).

(Hollow rod, 12 by 1.5 mm. (hole 1 mm.). Energy supplied, 6.6 watts. Curve *b*, fig. 70.)

This material is used to insulate thermo-couples, and conducts only at high temperatures. It is probably a mixture of magnesium oxide (see fig. 80) and silica. The temperature was probably 1200° to 1400°. The

emission spectrum is conspicuous for two regions of strong emissivity at 1.6 and 5 μ, respectively, with a deep depression at 3.5 μ. The emission bands at 1.6, 2.7, 5, 5.5, and 7.1 μ are not well resolved, but their presence can not be doubted.

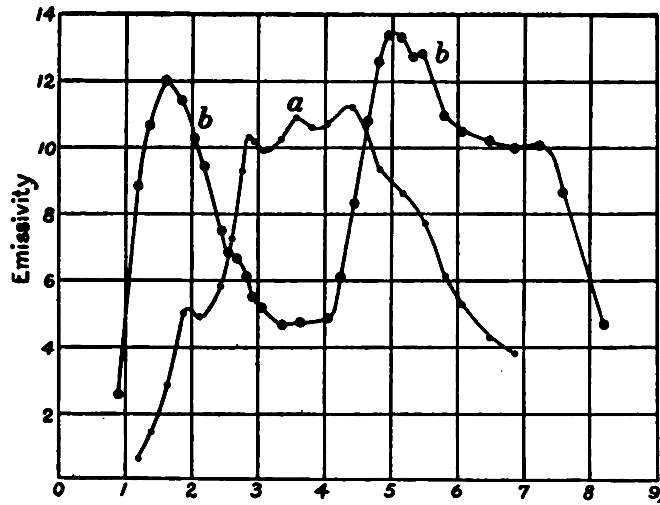


FIG. 70. — Glass (a); Magnesia.

GLASS (COBALT BLUE).

(Rod 12 by 2 mm. Energy supplied, 5.4 and 7.5 watts. Curves a and b, fig. 71.)

This rod was heated to a dull red. The emission spectrum is quite different from that of soft glass, but there are not such prominent bands

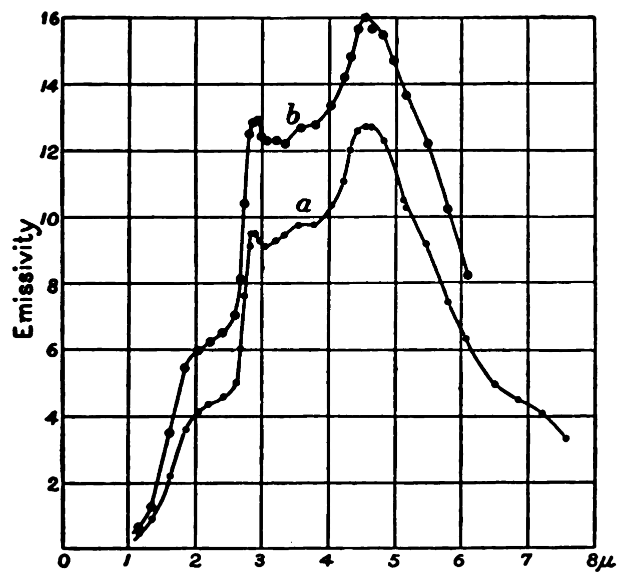


FIG. 71. — Cobalt glass.

as one might expect from a knowledge of the absorption bands at 1.6 and 2.2 μ to be noticed in fig. 37. The silicate band at 2.87 μ is prominent. Other bands occur at 2, 3.6, 4.6, and 5.5 μ, respectively.

SPODUMENE [$LiAl(SiO_3)_2$].

(From Pennington County, South Dakota. Irregular rod, 12 by 1.5 mm. Energy supplied, 5.7 and 9.5 watts. Curves *a* and *b*, fig. 72.)

This mineral contains cerium, lanthanum, and other "rare earths" as impurities. It can be melted in a blast flame. Considerable light was emitted, due to the presence of impurities. The emission spectrum shows the silicate band, sharply defined at 2.88 μ, with other bands at 2, 4.1, 4.5, 4.9, and 6.5 μ.

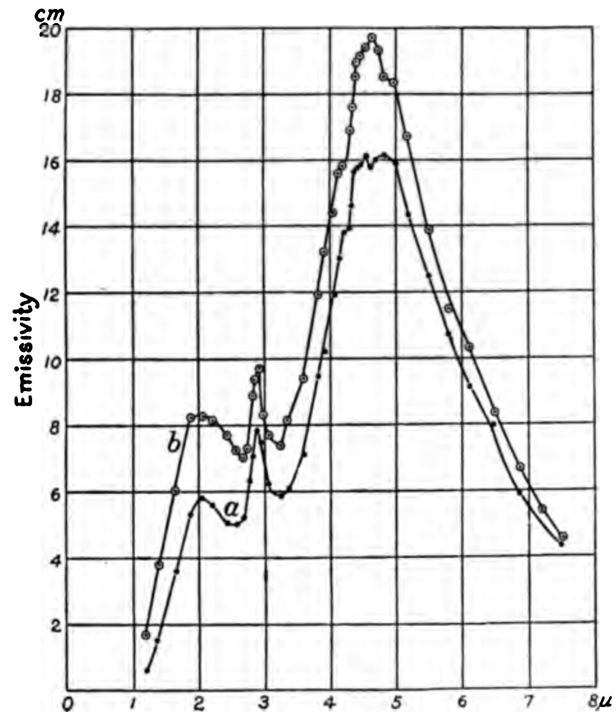


FIG. 72. — Spodumene.

BERYL [$Be_3Al_2(SiO_3)_6$].

(Rod 10 by 3 mm. Energy, 7 to 8 watts. Curve *a*, fig. 73.)

The rod was an opalescent milky glass, although the original crystal was a transparent green. The temperature was probably 1100°. The emission spectrum is unusual in appearance, with a sharp maximum superposed upon it at 2.8 μ. Other ill-defined maxima appear to be at 1.7, 2.4, 2.9, 3.6, 4.4, and 4.8 μ.

RUTILE (TiO_2).

(Flat plate 8 mm. long, tapering from 1.5 to 1.8 mm. wide and 0.25 mm. thick. Energy supplied, 6 watts. Curve *b*, fig. 73. Transmission, Carnegie Publication No. 65, p. 67.)

This mineral was heated to a bright red color corresponding to a temperature of perhaps 1000°. The emission spectrum shows maxima at 2.4, 3.2, 5,5, and 7.0 μ. The transmission spectrum is too low to show these as absorption bands; but the band at 3.1 μ is visible in the transmission spectrum of brookite (TiO_2). This substance is a good conductor of electricity at this temperature, but a very poor radiator of light rays.

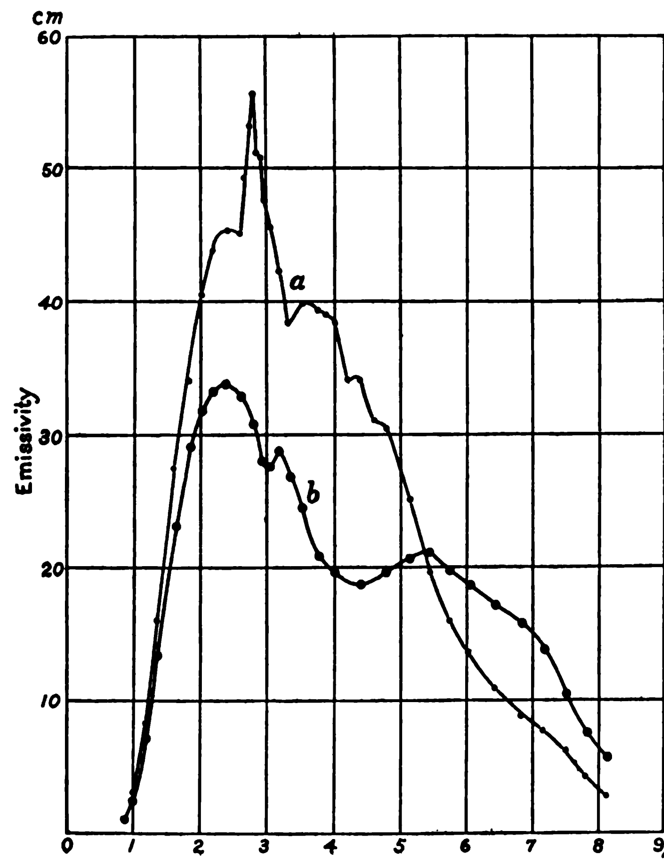


FIG. 73.—Beryl (*a*); Rutile.

TOPAZ [$(AlF)_2SiO_4$].

(Rod 13 mm. long, 2 to 2.5 mm. diameter. Energy supplied, 0.05 and 0.07 ampere,—probably 15 to 21 watts. Curves *a* and *b*, fig. 74.)

This rod was built up from the massive transparent mineral, and rendered conducting by the vapor set free from the albite cement used to secure the platinum terminals to the rod. The vapor left a narrow con-

ducting streak along one side of the rod, which heated the topaz. The curve is conspicuous for the sharpness of its emission bands, which occur at 1.4, 2.85, 4.1, 4.5, and 7.5 μ.

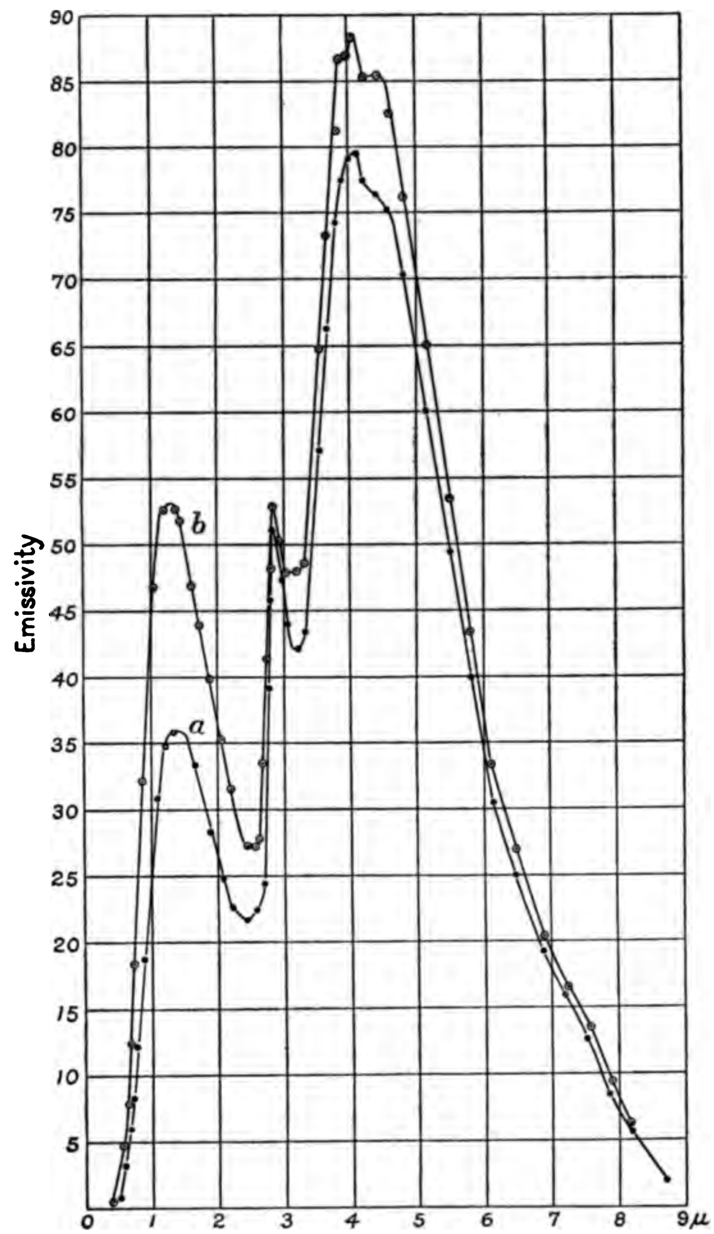


FIG. 74. — Topaz.

APATITE [$Ca_5F(PO_4)_3$].

(Rod 12 by 1.5 mm. Energy supplied, 9.3 and 11.8 watts. Curves *a* and *b*, fig. 75. Transmission, Carnegie Publication No. 65, p. 58.)

The emission spectrum shows emission bands at 2.9 and 4.5 μ. The rod was made from a dark massive specimen which may have contained silica, whence the band at 2.9 μ in both the emission and absorption spec-

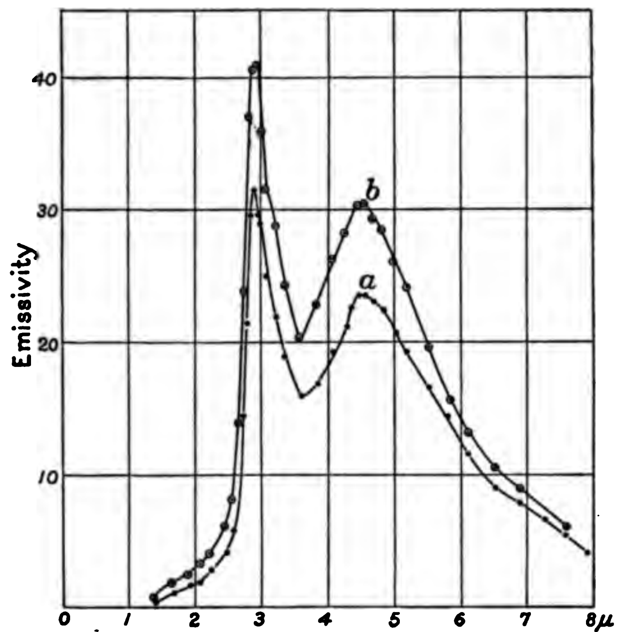


FIG. 75.—Apatite.

trum. On the other hand, many oxides, known to be free from silica, have a strong emission band in this region, from which it would appear that this band is characteristic of the oxides.

ALUMINUM OXIDE (Al_2O_3).

(Rod 14 mm. long, tapering from 2.5 to 3 mm. in diameter. Energy supplied, 0.025 and 0.115 ampere. Curves *a* and *b*, fig. 76.)

The rod was built up from the pure powder in an oxy-hydrogen flame. The emission curve is conspicuous for the great variation in intensity of its emission bands which occur at 1.4, 2, 3.1, 4.7, 5.2, and 7.5(?) μ. The emission curve differs but little from the one of topaz except that the latter has the silicate band at 2.85 μ. In fig. 65, curve *c* shows the radiation from a rod made from alumina and 1 per cent of feldspar, and curve *b*, fig. 65, gives the radiation from a rod made of alumina and 1 per cent of silica. In both cases the silica band at 2.87 μ is superposed upon the spectrum of the aluminum oxide.

Zirconium Oxide (ZrO_2).

(Rod 5 by 1.4 mm. Energy consumption, 3.5 (900°), 4.8, 5.8, 7.5 watts, curves *a*, *b*, *c*, *d*, fig. 77; 9.6, 12.1, and 14.5 (1400°) watts, curves *a*, *b*, *c*, fig. 78.)

The specimen examined was a fragment from a furnace wall. It probably contained some "binder," although from the curve for the pure

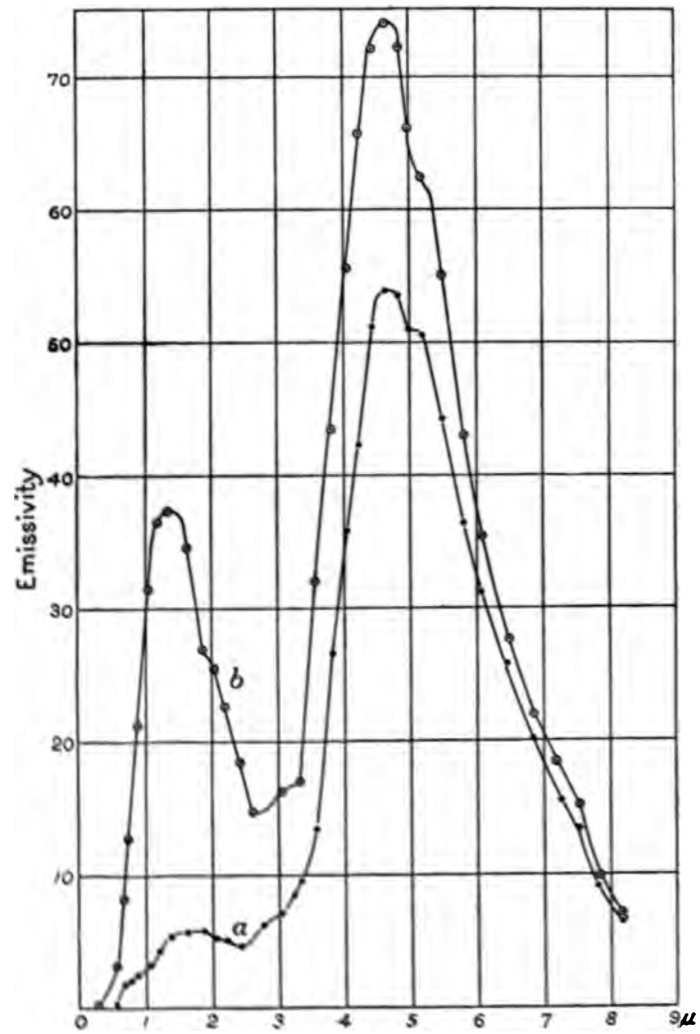


Fig. 76. — Aluminum oxide.

material (fig. 79) the foreign substance contributed but little to the emission bands. The fine platinum terminals were wound around the ends of the rod which was about 10 mm. long (5 mm. between the terminals).

The curves are conspicuous for their sharp emission band at 4.3 μ,

which remains superposed upon the continuous background even at a bright yellow heat, corresponding to a temperature of about 1400°.

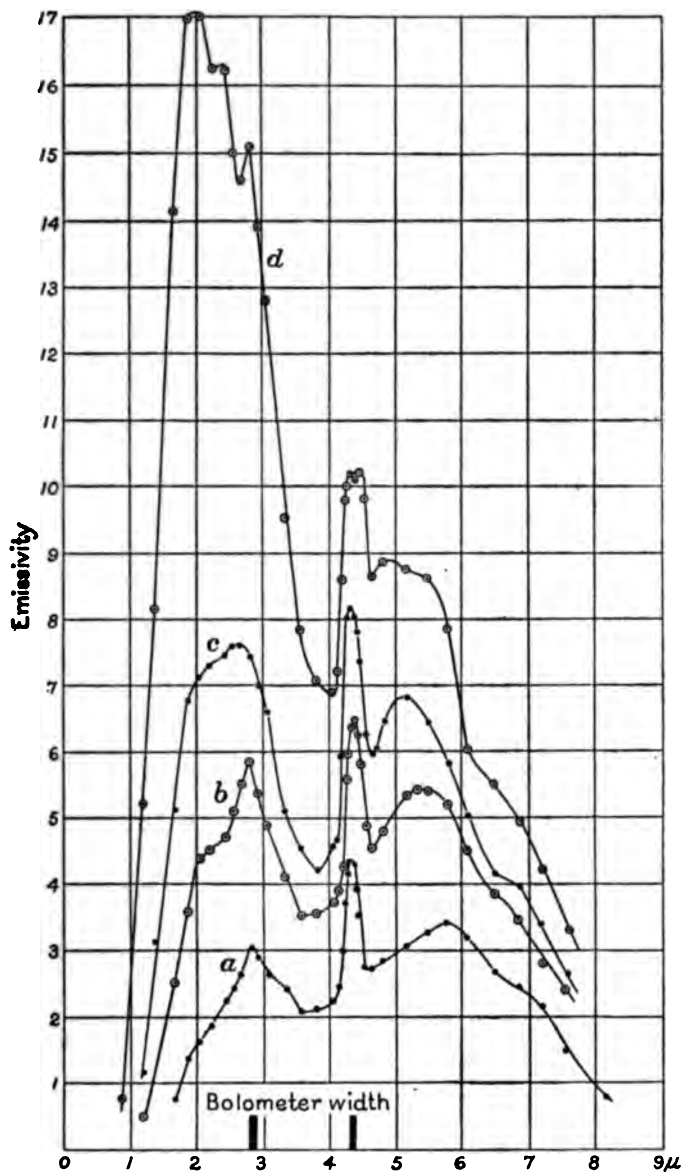


FIG. 77. — Zirconium oxide.

This series of energy curves is one of the best illustrations yet recorded of the gradual shift of the maximum of intensity of emission toward the short wave-lengths with rise in temperature. On an energy consumption

of 3.5 watts, the maximum of the envelope of these emission bands lies at 4 to 5 μ, and shifts steadily to the short wave-lengths, being at about 1.8 μ for an energy consumption of 14.5 watts. The pure oxide is not an efficient radiator of white light, and only becomes so when a small amount of cerium or thorium oxide is added, which combination is the Nernst glower already

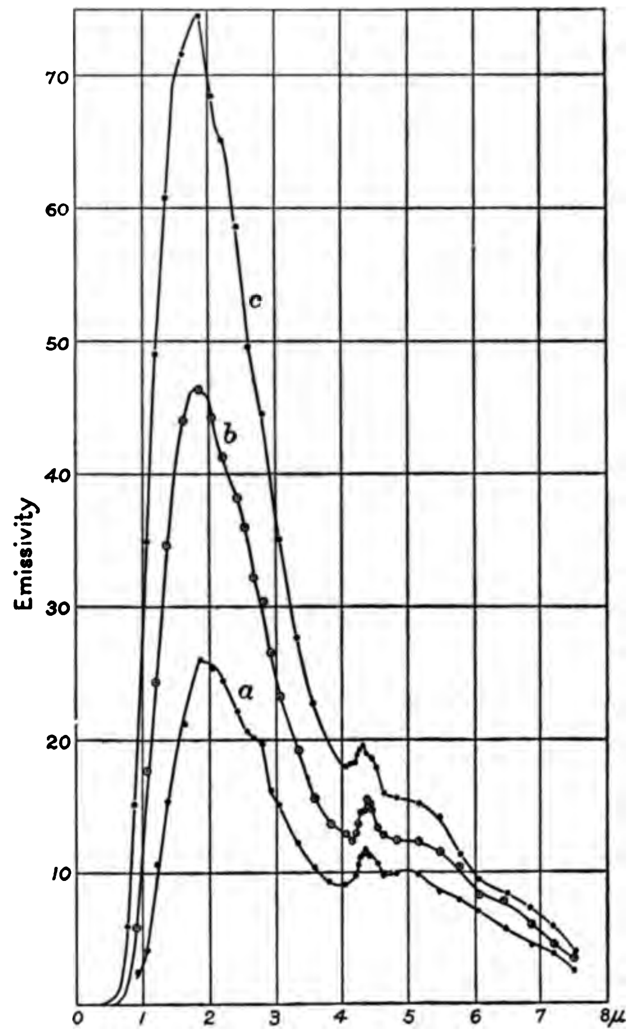


Fig. 78. — Zirconium oxide.

mentioned. Aside from the sharp emission lines at 2.8 and 4.35 μ there are wide hazy bands at 2 and 2.4 μ (appears on 7.5 watts), while from 5 to 6 μ there is a wide band which is evidently unresolved, the maximum shifting toward the short wave-lengths with rise in temperature. The extraordinary rapidity which characterizes the growth of the emissivity at

1.5 to 2 μ is worthy of notice. In one case where the ratio of emissivity at 4.3 μ for a given increase in energy is 50, it is almost 200 at 2 μ. In fig. 77 the curves are all for practically the same sensibility, 71, of the instrument. In fig. 78 the sensibility of the instrument was 60. These units are arbitrary, being the galvanometer deflections obtained by unbalancing the bolometer by a constant amount. For this substance the radiating rod was short and the voltage too low to be measured with the electro-static voltmeter. The ordinary voltmeter used affected the temperature of the radiator slightly, so that the energy consumption recorded is not so accurate as in the other observations.

EMISSION SPECTRA OF SOLIDS ON NERNST "HEATER TUBE."

In examining the radiation from solids placed upon a heater it is possible to have some of the radiation from the latter transmitted through the former. If the substance to be examined is in the form of a fine powder and the layer is from 0.5 to 1.5 mm. thick there is but little chance for the radiation to be transmitted from the heater. This fact enables one to study the selective emission of solids which can not be formed into solid rods, and is applied in studying the following list of substance.

ZIRCONIUM OXIDE (ZrO_2).

(Layer of oxide 0.8 to 1.5 mm. thick, on Nernst heater tube from which the clay covering had been removed. Fig. 79, curves *a*, *b*, and *c*.)

The zirconium oxide was heated to a dull red, which was somewhat lower than for the rod heated electrically (curve *a*, fig. 77). Curves *a* and *c* give the emission of different samples of the commercial product, the electrical properties of the latter being very bad when used for the body of a glower. Curve *b* shows the emission of a sample which has good electrical properties. It contained less than 0.01 per cent of silica, and was the purest obtainable sample. From this it is evident that the sharp maxima are not due to silica. The emission spectra are very similar and are conspicuous for two sharp emission bands, with maxima at 2.78 μ (curve *a*, maximum at 2.83 μ) and at 4.3 μ, respectively. Smaller maxima appear at 2, 2.4, 3.2, 4.7, and 5.4 μ. From a comparison of these curves with those given in figs. 77 and 78 it appears that in the latter sample the "binder" used, probably yttria, has but little influence upon the sharp emission bands.

MAGNESIUM OXIDE (MgO).

(Curve *c*, fig. 80.)

The magnesium oxide (curve *c*, fig. 80) spectrum shows two wide bands at 3 and 5.3 μ, respectively, with a smaller band at 2.1 μ. Somewhat similar conditions were observed in fig. 70.

In fig. 80, curve *a* gives the emission spectrum of the material used in a Nernst glower placed upon a heater-tube. The general outline, and

especially the emission bands, are to be observed in the radiation curves of the glower, given in fig. 57. In curve *b*, fig. 80, is shown the emission spectrum of a commercial "heater-tube." The covering is some refractory substance, perhaps containing aluminum oxide and a silicate binder. There is a sharp band at 2.85 μ and hazy bands at 4.7, 5.3, and 6.3 μ.

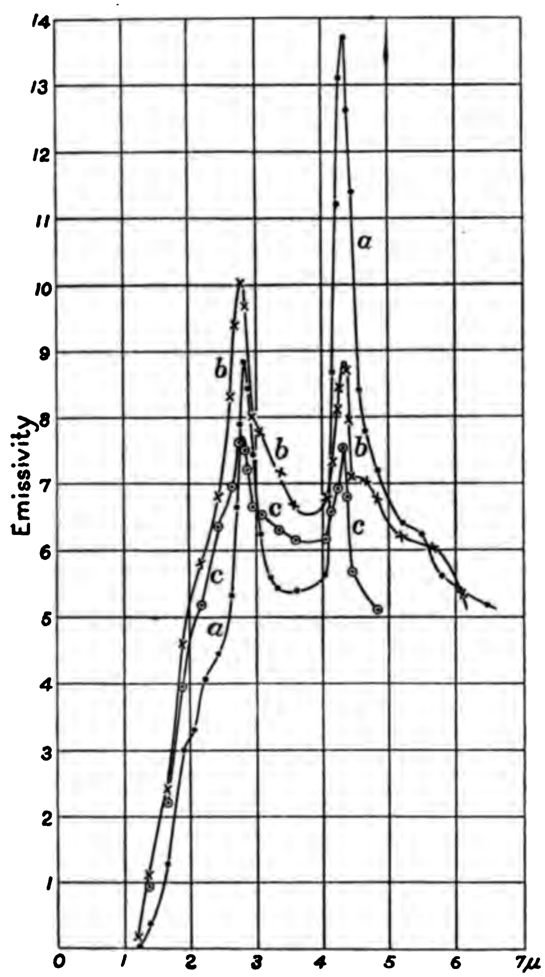


FIG. 79. — Zirconium oxide.

URANIUM OXIDE (U_2O_3); CERIUM OXIDE (CeO_2); THORIUM OXIDE (ThO_2).
(Curve $a = U_2O_3$; $b = ThO_2$; $c = CeO_2$; fig. 81.)

The uranium oxide is a greenish-brown powder which gives a smooth continuous spectrum with hazy maxima at 2.8 and 3.4 μ, respectively.

The thorium oxide, curve *b*, shows no marked emission bands, and the whole spectrum is suppressed to 7 μ. Beyond this point the emissivity is

high, corresponding closely to that of a complete radiator, as was shown by Rubens, using a gas-mantle of this material.

The cerium-oxide curve shows a strong emission at 2 to 3 μ, as was found by Rubens, with possible bands at 4.4 and 7.5 μ. It was shown by Rubens that beyond 7 μ the emissivity approaches that of a complete radiator.

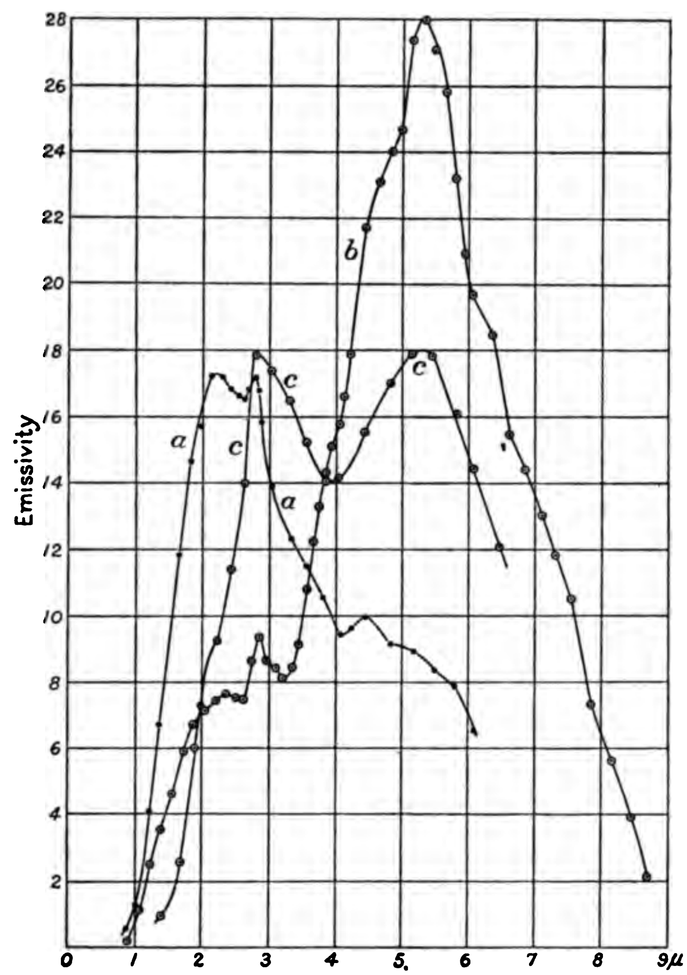


FIG. 80.—Nernst glower (*a*); Nernst "heater-tube" (*b*); Magnesium oxide.

In the Auer gas mantle (90 per cent ThO_2 + 1 per cent CeO_2) the cerium oxide acts as a sensitizer does on a photographic plate, by making an absorption band in one region of the spectrum without affecting the rest.

The energy curve of an electrically heated filament of the same composition as the Auer mantle is given in the Bulletin of the Bureau of Standards, vol. 5, No. 2, 1908. The energy curve is entirely different

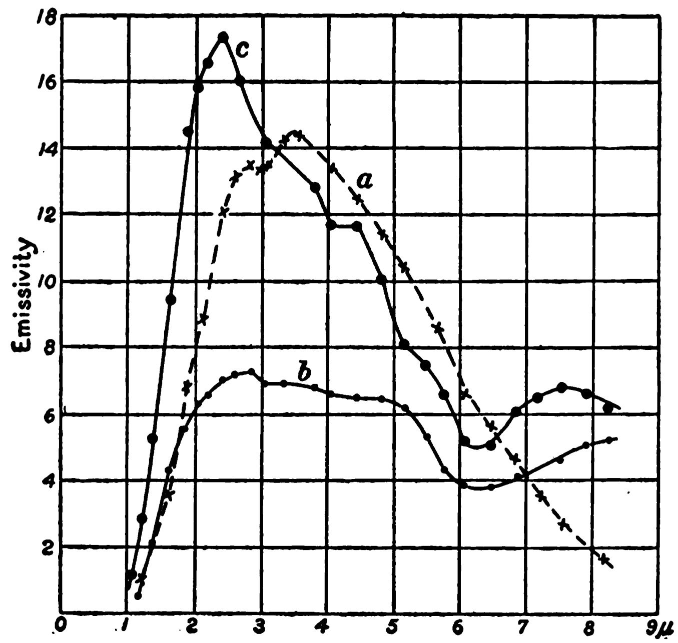


FIG. 81. — Uranium oxide (a); Thorium oxide (b); Cerium oxide.

from that of the Auer mantle, being similar to that of the Nernst glower. This is no doubt due to the greater thickness of the radiating layer, which emits a more nearly saturated radiation in the region of 1 to 3 μ, as well as in the remainder of the spectrum.

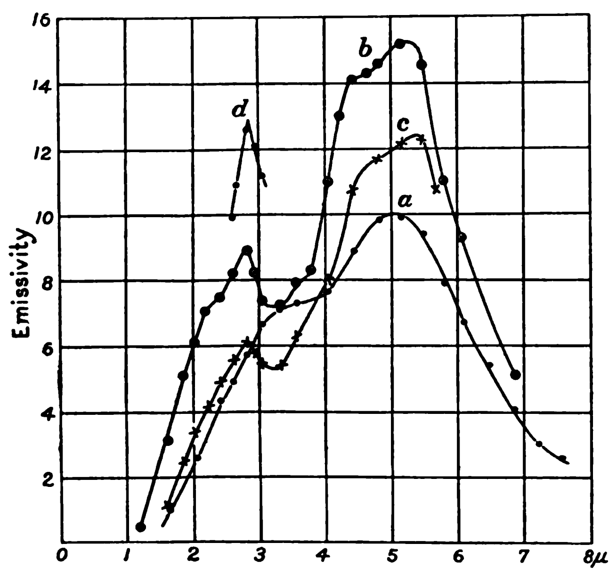


FIG. 82. — Beryllium oxide (a); Silica (b), (c); Feldspar.

BERYLLIUM OXIDE (BeO); SILICON OXIDE (SiO_2); VANADIUM OXIDE (V_2O_5).

(Curve a = BeO; b and c = SiO_2; fig. 82.)

The beryllium-oxide emission spectrum is smooth, with two wide maxima at 3.5 and 5 μ, respectively. The temperature was such that a faint red showed through the interstices of the layer of white oxide.

The silicon-dioxide (quartz, French flint) curve shows bands at 2.2, 2.83, 3.7, 4.4, and 5.3 μ, which coincide with the absorption bands (see Carnegie Publication No. 65, p. 21). For curve c the layer of silica was 1.4 mm. For curve b (thinner layer) the surface temperature was about 800°.

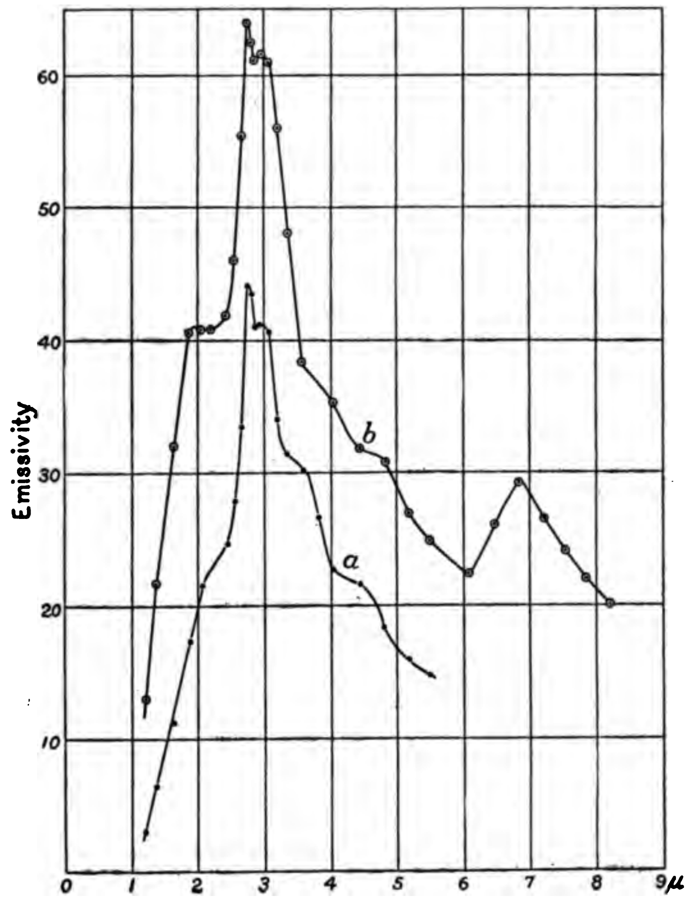


FIG. 83.—Yttrium oxide.

The vanadium oxide in the preliminary examination showed no emission bands. The substance is a black powder, which melted at a low red heat, and no further examination was made into its emission spectrum, which was similar to that of carbon. Curve d, fig. 82, shows the emission band of pure feldspar placed on the heater.

Yttrium Oxide (Y_2O_3).

(Curves *a* and *b*, fig. 83; curves *a*, *b*, *c*, fig. 84.)

The surface color in the two cases (fig. 83) was a deep and a bright red, corresponding to a temperature of 900° to 1000°. The two curves are similar in appearance, showing emission maxima at 2, 2.76, 3, 3.6, 4.6, and 6.9 μ, respectively, the latter band being unusually sharp. It will be

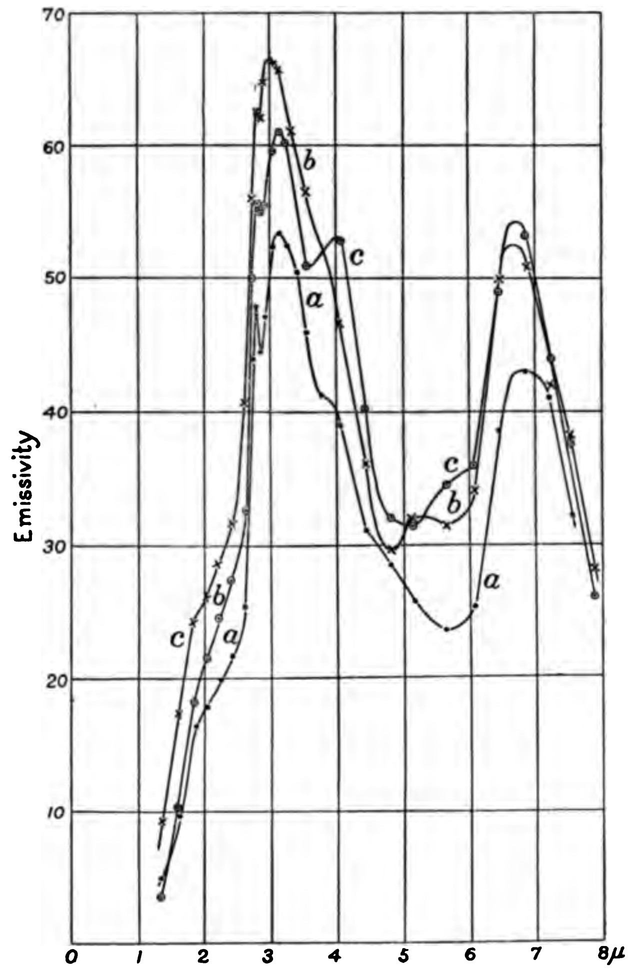


Fig. 84. — Yttrium oxide.

shown presently, in fig. 92, that this sharp band may be due to a suppression of the radiation at 6 μ, caused by a band of metallic reflection at this point. However, bands of metallic reflection are not common at these short wave-lengths, so that the maximum at 6.9 μ may be a true emission band.

In fig. 84 are shown the emission curves of three additional samples of

yttrium oxide, of unknown purity, all of which were a beautiful yellow color, as compared with the sample given in fig. 83, which was a yellowish-white. These samples were obtained by fractional precipitation from the sulphate of yttrium by means of oxalic acid. The precipitation, however, was not carried out to the extent of obtaining yttrium, erbium, and ytterbium oxides separately. In these curves the prominent bands of fig. 83, with maxima at 2 and 2.75 μ, are suppressed, and the small bands of the latter at 3 and 6.8 μ are the most prominent. These three samples were heated so that the surface appeared a dull red, the sample for curve *b* being the hottest. The emission bands occur in two groups, at 3 and 6.8 μ, respectively, just as was found in the oxides of zirconium and magnesium. There are sharp maxima at 2.8, 3.15, and 6.75 μ, and smaller bands at 2, 3.9, and 5.2 μ, respectively.

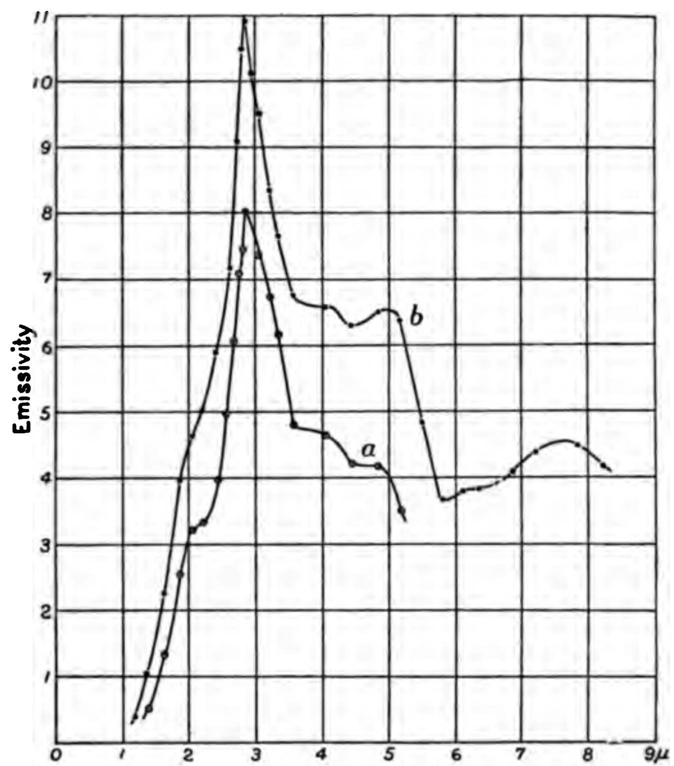


FIG. 85. — Erbium oxide.

ERBIUM OXIDE (Er_2O_3).

(Curves *a* and *b*, fig. 85.)

Curve *a* shows the emission of a layer of the oxide formed by decomposing a solution of the nitrate on a strip of platinum, heated electrically. Curve *b* gives the distribution of energy of a layer of the oxide on a heater-

tube. The two spectra are similar, with a sharp emission band at 2.85 μ. Other maxima appear at 2, 3.2, 4.1, 5, and 7.5 μ. The general outline of the spectrum is similar to that of yttrium.

Neodymium Oxide (NdO); Manganous Oxide (MnO).

(Curve *a*, NdO; curve *b*, MnO; fig. 86.)

The neodymium oxide was deposited in a thick layer upon a strip of platinum, by evaporation from a solution of the nitrate. The radiation curve shows maxima at 3, 4.4, and 4.83 μ. Beyond 6 μ the emissivity is strong and not unlike that of cerium and thorium. The scale of emissivity is one-half of the curve for MnO.

Fig. 86. — Neodymium oxide (*a*); Manganous oxide.

The manganous oxide was a grayish-brown color. The thickness of the layer upon the "heater-tube" was about 1.2 mm. The radiating surface was a dull red. The spectral radiation curve is uniformly smooth throughout its whole length, with but a slight depression at 3.2 μ to be noticed in numerous oxides. In these two curves the sensibility of the instrument is different, as is frequently the case.

Zinc Oxide (ZnO); Lead Oxide (PbO).

(Curve *a*, ZnO; curve *b* and *c*, litharge (PbO), curves *e* and *f*, platinum; fig. 87.)

The zinc oxide became a yellowish-green on heating, resuming its former white color on cooling. In spite of this selective emission in the visible spectrum, the distribution of energy in the infra-red is uniform, with the usual depression at 3.2 μ. Lead oxide ("litharge") melts at a low temperature. On heating the color changes from orange to deep red. Curve *b*, fig. 87, shows the distribution of energy for the oxide after it had melted into a smooth mass and solidified. Curve *c* shows the emissivity

from an unmelted surface. The depression at 3.3 μ is marked, and at 5.5 μ there is a possible emission band. The thickness of the layer was at least 1.2 mm.

Curves *e* and *f* show the emission of a strip of platinum. No depression appears at 3.3 μ, from which it would appear that the depression at 3.3 μ is a characteristic of the oxides and not due to absorption in the instrument.

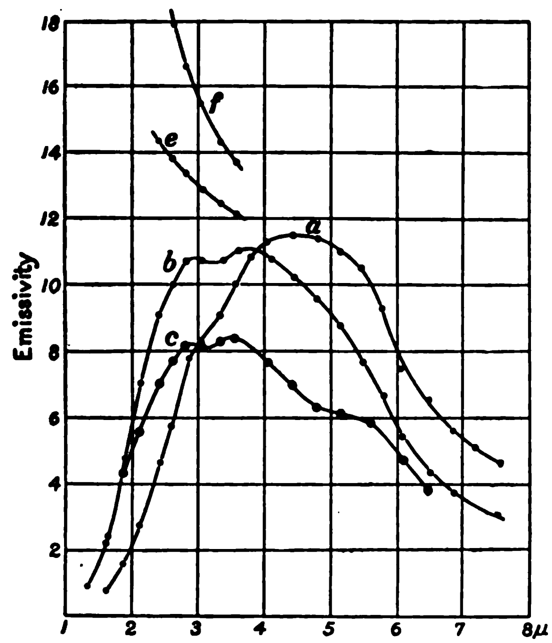


Fig. 87. — Zinc oxide (*a*); Lead oxide (*b*), (*c*); Platinum.

Iron Oxide (Fe_2O_3); Copper Oxide (CuO).

(Curves *a* and *b*, Fe_2O_3; curves *c*, *d* *e*, CuO; fig. 88.)

The iron oxide used was red hematite, or "rouge." The layer on the heater-tube was 1.5 mm., heated to redness, 800°. The energy curve is smooth, except a depression at 3.2 μ. The copper-oxide layer was 1.5 mm., heated to a deep red. The energy curve is smooth, except the slight depression at 3.2 μ.

Cobalt Oxide (Co_2O_3); Chromium Oxide (Cr_2O_3); Stannic Acid (SnO_2).

(Curve $a = Co_2O_3$; curves *b* and *c*, Cr_2O_3; curve *d*, SnO_2; fig. 89. Sensibility 80, 85, and 73, respectively. Temperature 800° to 900°).

The cobalt-oxide curve is smooth throughout, except the depression at 3 μ.

Chromium oxide is green in color, and emits a fairly smooth spectrum with a possible maximum at 5 μ. The depression at 3.2 μ is prominent.

Stannic acid is grayish-white in color, but, unlike many of the white

oxides, it emits a continuous spectrum. The depression at 3.2 μ is small. The transmission bands in cassiterite, SnO_2, were found to be small.

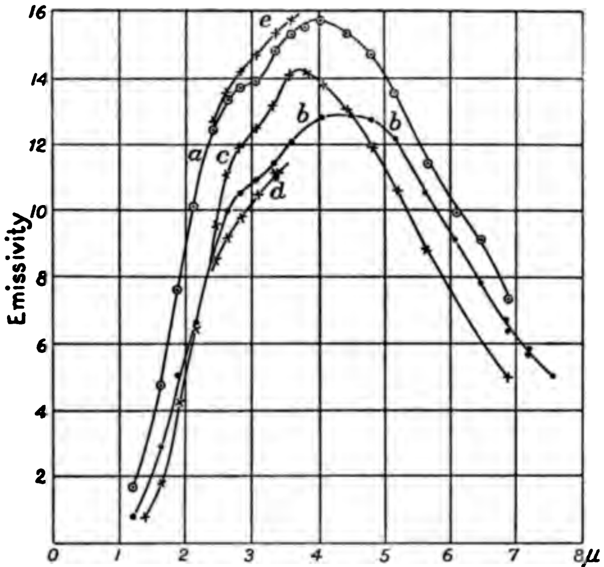


FIG. 88. — Iron oxide, (a) (b); Copper oxide.

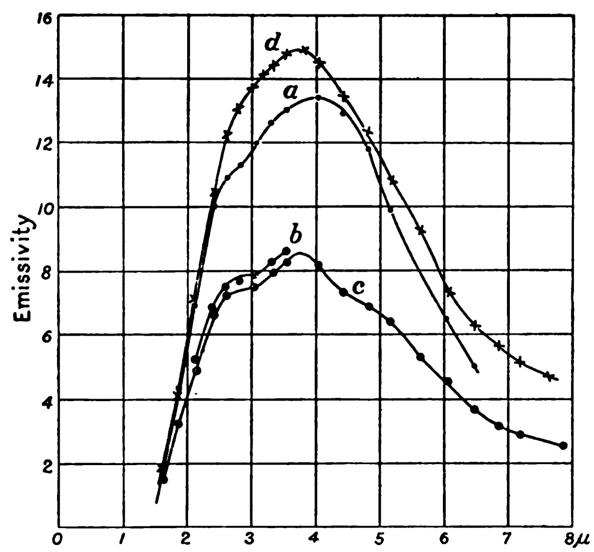


FIG. 89. — Cobalt oxide (a); Chromium oxide (b), (c); Stannic oxide.

NICKEL OXIDE (NiO); CALCIUM SULPHATE ($CaSO_4 + 2H_2O$).

(Curves *a*, *b*, *c* = NiO; curve *d* = $CaSO_4$; fig. 90. Temperature about 900°. Transmission, Carnegie Publication No. 65, p. 18; curve *b*, fig. 2.)

The nickel-oxide surface was rougher than for the other oxides, hence not so uniformly heated. At the highest temperature the de-

pression at 3.3 μ is very marked, while at the lower temperatures it is not so deep.

The calcium sulphate used was a thick, smooth layer of "plaster of paris," which dehydrated (at least in part) at the red heat used. The emission bands at 2, 3.2, 4.65, and 6.3 μ coincide in intensity and position with the absorption bands found in previous work (see Carnegie Publication No. 65, fig. 4). The band at 4.65 μ is shifted from its position at

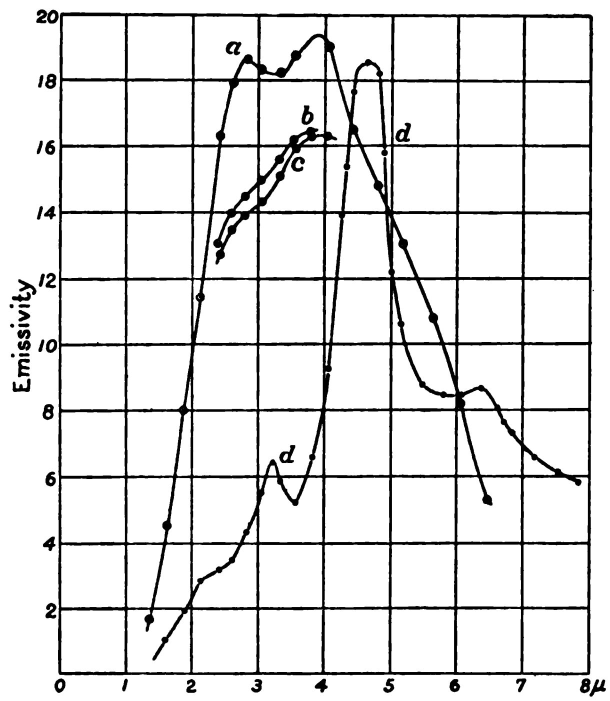


FIG. 90.— Nickel oxide (a), (b), (c); Calcium sulphate.

4.55 μ in anhydrite ($CaSO_4$), but coincides with the partially dehydrated selenite ($CaSO_4 + 2H_2O$) given in Carnegie Publication No. 65, figs. 3 and 4.

The absence of the band usually found at 2.8 μ may indicate that it is not due to water. Paschen found an emission band of water at 2.83 μ in the Bunsen flame.

CALCIUM OXIDE (CaO); TRICALCIUM PHOSPHATE [$Ca_3(PO_4)_2$].

(Curves *a* and *b* = CaO; curve *c* = $Ca_3(PO_4)_2$; fig. 91.)

The surfaces of these two substances were at a dull red heat. The calcium-oxide layer was somewhat cracked, but not sufficient to interfere with the radiation. The layer of oxide in each case was about 1.2 mm.

The calcium-oxide emission curve is conspicuous for its two sharp maxima, at 2.8 μ and at 4.75 μ, respectively, and a high emissivity at 8 μ,

which is not unlike that of cerium and thorium oxides, observed by Rubens. Smaller bands appear at 2.4, 3.3, and 4 μ. The calcium oxide was heated to a bright red before mounting it upon the heater-tube, and was apparently free from the carbonate (fig. 92). Since there are no emission bands belonging to that substance, it appears that the water used in making the CaO into a paste was entirely expelled.

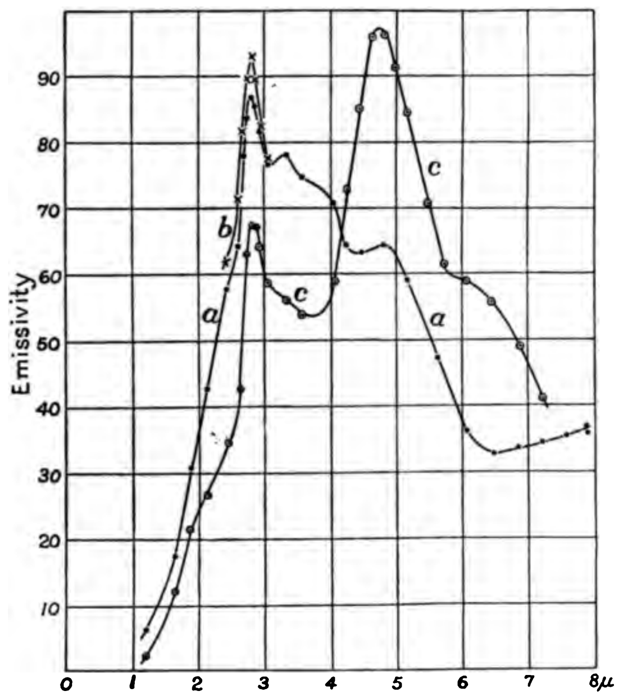


Fig. 91. — Calcium oxide (a); (b); Tricalcium phosphate.

The tricalcium phosphate has two marked emission bands, at 2.85 and 4.75 μ, respectively, and smaller bands at 2 μ and 6.2 μ. The emission spectrum is unusually similar to that of apatite (fig. 75).

A chemical analysis of calcium oxide, by Dr. H. C. P. Weber, showed no weighable amount of silica. This shows that the band at 2.8 μ is not due to silica.

Calcite ($CaCO_3$).

(Curves *a* and *b*, fig. 92. Transmission, Carnegie Publication No. 65, p. 70.)

The sample examined was a layer of finely ground white marble. The surface color in the two cases corresponded to about 900° and 1000°, respectively. The emission curve is of interest on account of the two types of emission it contains. In the region of 6.7 μ calcite has a band of strong selective, "metallic," reflection. In this region of the spectrum the emissivity is proportional to the reflecting power, thus placing in the class with

metals. Here the emission is actually suppressed, and we have an emission minimum instead of a maximum, as will be described in the following chapter. In the remaining part of the spectrum the emission is propor-

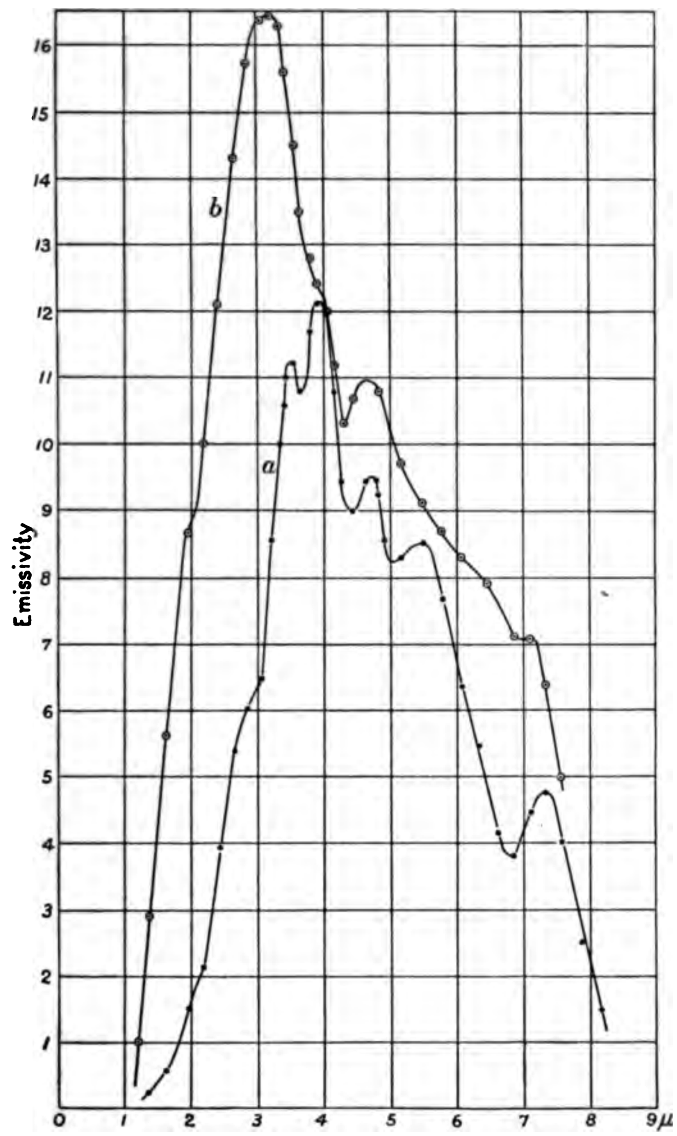


FIG. 92. — Calcite.

tional to the absorption. The emission bands at 2, 2.7, 3.5, 3.9, 4.7, and 5.5 μ coincide with the absorption bands previously observed. The apparent maximum at 7.3 μ is due to the suppression of the radiation at 6.8 μ. This fact can, of course, only be determined from a knowledge of

the reflecting power of the substance under examination. The maximum reflection and the minimum emission do not coincide on account of the high reflecting power on the side toward the long wave-lengths, which suppresses the emission curve, thus shifting its minimum farther into the infra-red. The only other example heretofore investigated is by Rosenthal,[1] for quartz, which will be described in the next chapter. The band at 4.7 μ is of interest since it occurs in CO and CO_2 in the vacuum tube radiation (see Carnegie Publication No. 35), and is in common with the *carbonates* and the *sulphates.*

RELATION BETWEEN EMISSIVITY AND ENERGY CONSUMPTION.

The substances just described must have one or both of two kinds of spectral energy distribution, due (1) to the general absorption which is present to some extent, however small, and which gives rise to a continuous spectrum, and (2) to bands of selective absorption which give rise to emission bands.

The object in examining the isochromatic radiation curves of the aforesaid solids is to determine whether or not the observed sharp emission bands behave like spectral lines, or like bands which include a considerable portion of the spectrum. If the observed bands behave like those of a gas, the emission must be proportional to the energy supplied. If the radiation is similar to the complex and highly damped emission of a solid, *e.g.* platinum, the isochromatics can not be straight lines, but must be similar to those of platinum.

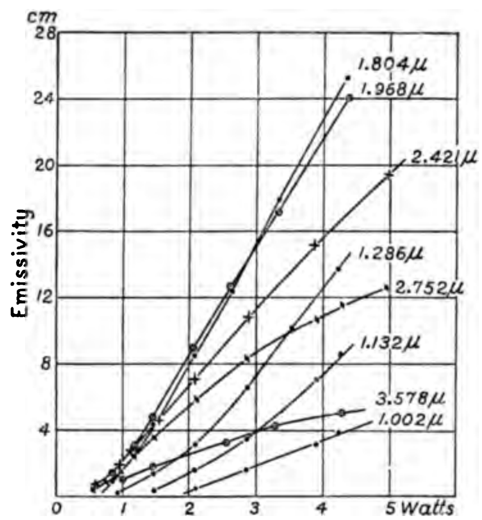


FIG. 93. — Isochromatic radiation curves of platinum.

A complete radiator emits energy, however small the amount, of all wave-lengths, whatever its temperature above the absolute zero. The isochromatic energy curves must, therefore, all begin at the origin of the energy axis; and they may have a double curvature. This is well illustrated in fig. 93 for the isochromatic radiation curve of platinum at 2.752 μ. The platinum strip was 50 by 1.5 by 0.02 mm., in an exhausted glass bulb, with a fluorite window. In this figure the graphs of wave-lengths $\lambda = 1.804\ \mu$ and $\lambda = 1.968\ \mu$ intersect at 2.8 watts, showing that the maximum of the energy curve lies between these two wave-lengths; temperature about 1100° C.

[1] Rosenthal: Ann. der Phys. (3), **68**, p. 791, 1899.

It is interesting to note that the point of inflection in the curves occurs when the isochromatic wave-length is identical with the wave-length λ_{max}, (E_{max}). This, of course, is due to the well-known property of spectral emission of a complete radiator, or a metal, in which the emissivity in the short wave-lengths increases more rapidly than on the long wave-length side of the maximum emission.

On the other hand, the graph showing the relation between the emissivity of a spectrum line and the energy supplied should intersect the energy axis at a distance from its origin, corresponding to the energy (a finite amount) required for excitation, which is different for different spectral lines. This is a well-known property of spectral lines, being independent of the wave-length.

Furthermore, if we follow the common line of reasoning (see Kayser's Spectroscopy, vol. II, pp. 59, 245, and 331) and consider the separate lines as a part of an energy curve, obtained by drawing the envelope through the highest points of the separate emission bands, then the maximum of the envelope must shift toward the short wave-lengths with increase in energy consumption, and the slant of the isochromatics must be similar to those of platinum (fig. 93). It is difficult to conceive how this is possible with discrete spectral lines which require the application of a certain amount of energy to excite them. The change of the emission curves of the Nernst glower from a discontinuous into a continuous one has already been noticed. They illustrate this envelope type of energy curve just mentioned. But it seems more probable that this is due to the rapid growth of the general emission of the intervening frequencies, which, with a doubtful broadening of the emission bands, obliterates the selective emission at high temperatures. In fig. 94 are shown the isochromatic energy curves of a Nernst glower, the values being taken from fig. 57. In fig. 95 are given a series of isochromatics for a 110-volt glower 1.4 cm. long and 1.4 mm. diameter. The current was supplied from a 2000-volt 600-watt transformer on a 110-volt circuit. The energy supply was regulated by means of resistances in the primary.

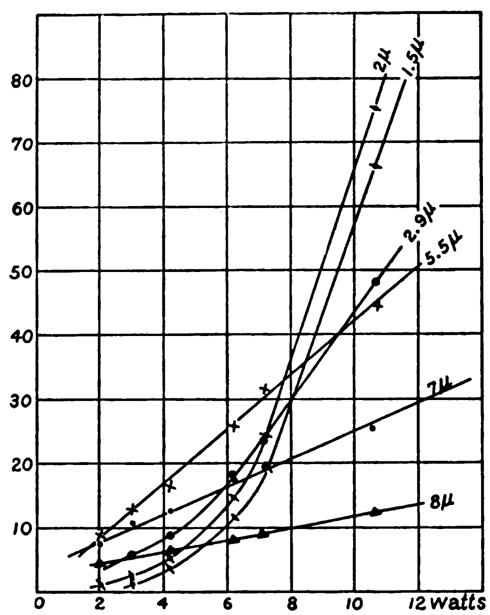


Fig. 94. — Isochromatic radiation curves of Nernst glower.

The voltage was obtained with a multiple-cell electrostatic voltmeter. The curves for the intensest part of the spectrum pass through a double curvature and have the general outline of that of platinum. The normal burning is 80 watts and above that point the isochromatics appear to

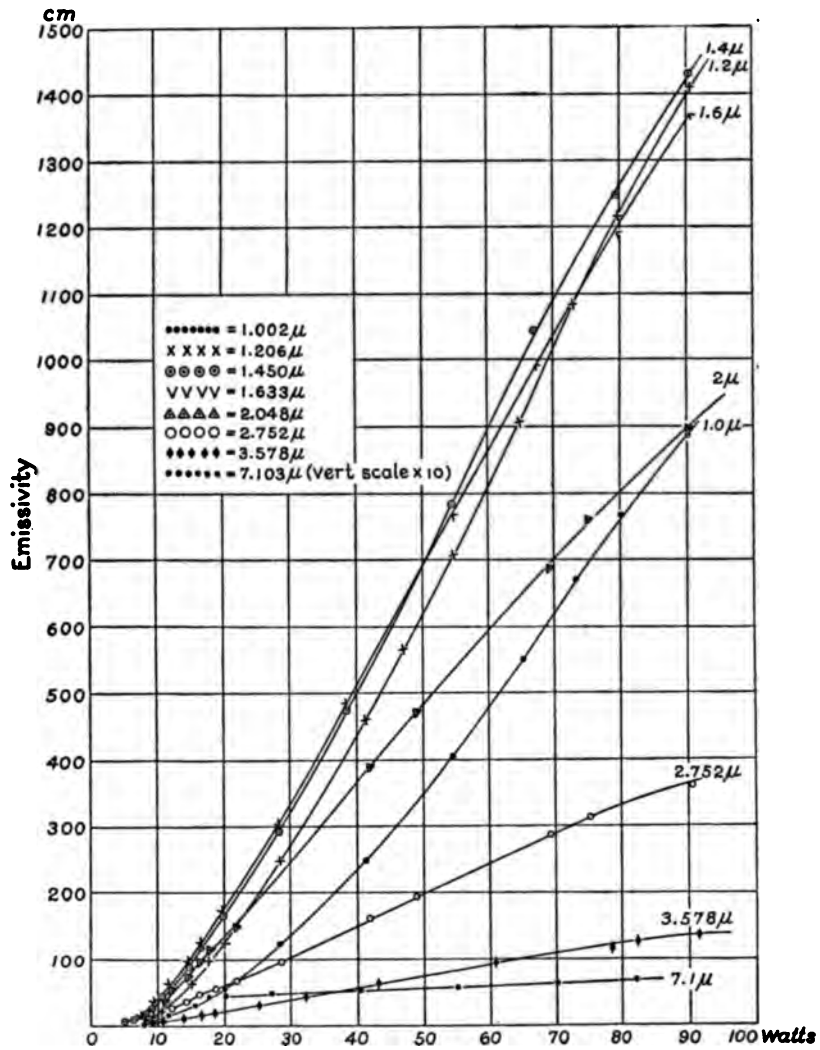


FIG. 95.—Isochromatic radiation curves of Nernst glower.

show a slight increase in curvature. The intersection of the graphs for wave-lengths $\lambda = 1.206\ \mu$ and $\lambda = 1.633\ \mu$ at 73 watts[1] shows that the maximum of the spectral energy curve for this power consumption lies between

[1] None of the isochromatics, given in this paper, have been corrected for slit-width, which would change the observed energy consumption a few per cent.

these two points, as previously observed. This method of locating the maximum eliminates the correction for slit-width, and is an independent proof of the previous observations that the maximum of the energy curve for normal burning (80 watts) can not lie at such short wave-lengths as was observed by previous investigators. This, of course, is on the assumption that the glowers were of the same material, the base of which is zirconium oxide with a small per cent of thorium or yttrium oxide.

In Carnegie Publication No. 35, p. 318, it was shown that in the case of vacuum-tube radiation the intensity of the emission lines is proportional to the energy consumption. The graphs there obtained, showing the relation between current and emissivity of a spectral emission line, are curved, due to the fact that Ohm's law does not hold for the vacuum-tube discharge. For the present examination, instruments were available to measure the energy consumption, when the graph ought to be a straight line, provided the partition of the energy emitted is in discrete lines. As a typical, selectively radiating solid, oligoclase was chosen on account of its sharp emission bands, and also on account of its homogeneity. A rod 2.5 cm. long and 2 mm. diameter was prepared in an oxyhydrogen flame. The spectrometer slit was reduced to 5 mm. in length, which permitted the entrance of radiation from only about 5 mm. of the central part of the rod, which was a perfectly clear glass, free from air-bubbles. At the highest temperatures this central part showed a peculiar faint white "luminescence" similar to the intense white noticeable in quartz when heated in the oxyhydrogen flame. The rod was thickened at the ends which seemed to prevent internal reflection of the radiation from the platinum terminals.

The distribution of energy from the central portion of this rod is shown in curve *c*, fig. 66, on 29.4 watts. The ends of the 0.3 mm. platinum terminals within the glass rod were red hot. The rod was viscous, indicating a temperature of at least 1100° to 1200°; but no light was emitted other than the hazy white glow already mentioned, which is in marked contrast with the radiation from the platinum electrodes. A similar example is given in Wood's Optics, page 457, where it is stated that sodium sulphate, in a loop of platinum wire, heated in a blast lamp, emits but little light, although the wire glows vividly.

In fig. 96 are given the isochromatic emission curves of oligoclase at wave-lengths 2.048, 2.905, 4.445, and 6.082 μ, respectively, for different values of power consumption. The graphs are for the same rod, under the same conditions of galvanometer sensibility and distance of the radiator from the silt. Two additional series of observations on different days, and using different adjustments, were made at wave-length 2.905 μ. Only one of these graphs was parallel with the one given in fig. 96, showing that there is a variation in the slant of the isochromatic curve, under different conditions. It will be noticed that, throughout the range investigated, the change in emissivity is proportional to the energy supplied, just as is true

of gases. It is possible that for some wave-lengths the thickness of the radiator was not sufficient to emit a saturated radiation, and this may explain why the emissivity at 2.048 μ apparently does not follow the same law as do the other emission bands. In order to have a displacement of the maximum of emission, just as is known for solids emitting continuous spectra, it is necessary that the intensity of the emission at the short wave-lengths increase more rapidly than it does in the long wave-lengths. The 2.048 μ isochromatic slants only a little less from the normal than does

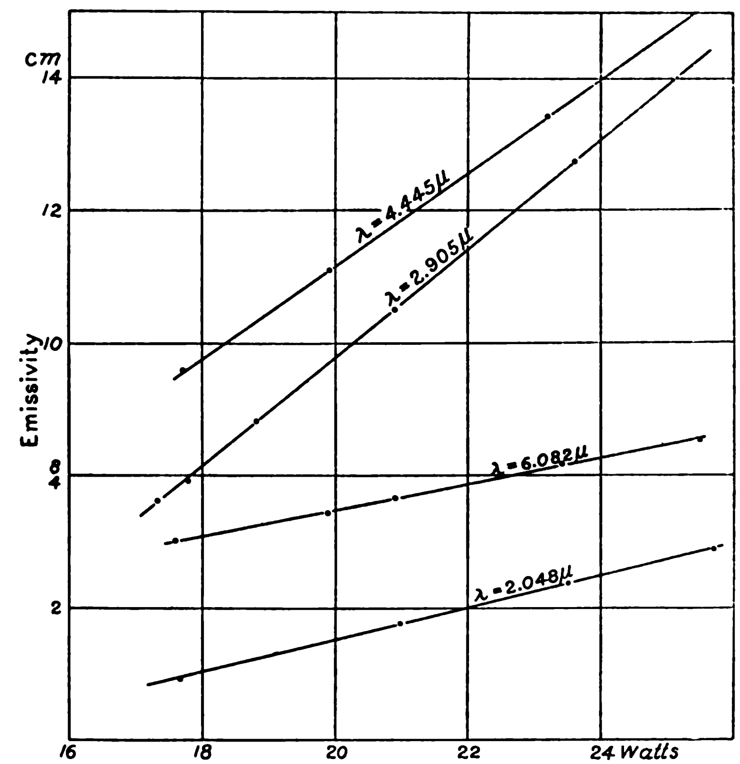


FIG. 96. — Isochromatic radiation curves of oligoclase.

$\lambda = 6.082\ \mu$. In this region of the spectrum there is a weak general absorption, while the other wave-lengths are the maxima of selective emission (absorption) bands, and it is possible that what corresponds to the emissivity constant a of a complete radiator is different for the two kinds of radiation found in this substance. It is possible that the isochromatic at 2.048 μ undergoes a sudden change, curving sharply upward, at a higher temperature. The same is true of the platinum isochromatic at 1 μ. In fact, it appears that the emissivity at 2.048 μ must suddenly change in intensity, unless oligoclase is entirely different from the other substances examined; for, like the others, in the oxyhydrogen flame, it emits an intense

white light, although, as shown in curve *c*, fig. 66, the emissivity at 2 μ is still weak when the temperature is close to the melting-point.

In oligoclase it is not possible to locate so definitely, if at all, the position of the maximum of the envelope by the intersection of the isochromatics; for the lines show no tendency to curve, as in platinum, although at closely the same temperature. By the extrapolation of the 2.9 μ and the 4.4 μ isochromatics, the intersection (obtained after correcting for slit-width) is found to be at about 8.5 watts. The maximum emission would then lie at about 3.5 μ, which is the position of the maximum of a complete radiator at 850° abs. (580° C.). On 29.4 watts, when the oligoclase was already viscous, indicating a temperature of 1100° to 1200° C. (melting-point 1300°), the maximum emission would have to lie at a much smaller wave-length than 3.5 μ, say at 2 μ, which is inconsistent with the observations that the emission curve is but little different in outline from those obtained at lower temperatures, — there being no indication of a shifting of the energy distribution. It would therefore appear that it is not permissible to consider the envelope, drawn through the emission maxima, as a criterion for judging the temperature of a substance like oligoclase. On the whole, it appears that the general emission, as distinguished from the bands of selective emission, is less intense in oligoclase than in most of the other silicates studied. Such a substance, if it would withstand high temperatures, would most nearly approach the ideal light producer. For, since the absorption coefficient is small throughout the region, to 3 μ, where, in a continuous spectrum, the greatest amount of energy is emitted, the emission spectrum would remain discontinuous, and only at the highest temperatures would the general emission become of importance, when a large amount of the energy radiated would be of wave-lengths affecting the eye.

SUMMARY.

In general, the results on the oxides furnish an excellent illustration of the shifting of the maximum of intensity of emission toward the short wave-lengths with rise in temperature, just as is known for solids emitting continuous spectra. In this respect the various emission curves of zirconium oxide are particularly conspicuous. In addition to what may be termed "general emission," in which the maximum shifts with rise in temperature, the curves of zirconium oxide are unique in having a sharp band of "selective emission" which does not shift nor broaden with rise in temperature. The results are not unlike those obtained by Anderson [1] for erbium oxide, in the visible spectrum. He found that the emission spectrum was not continuous, but consisted of bright bands superposed upon a continuous faint background. With rise in temperature the bands became more hazy in outline, and at very high temperatures the spectrum became continuous. If, according to Stark's theory, the continuous spec-

[1] Anderson: Astrophys. Jour., 26, p. 73, 1907.

trum is due to the presence of a large number of free electrons, this is to be expected. At low temperatures the electrical conductivity is small, and the emissivity is confined to particular bands caused by certain groups of electrons. With rise in temperature more electrons, extending over a wider range of wave-lengths, are excited to activity and the separate emission bands become merged into a continuous spectrum. This is not always true, however, in the present work. For example, the sharp emission band of zirconium oxide at 4.3 μ seems to retain the same intensity, superposed upon a continuous background of increasing intensity, irrespective of the temperature. In fact, many of the emission bands are as sharp as those found in gases.

Many of these oxides have an emission band in common in the region of 2.85 μ, from which it would appear that this band may be due to the oxygen atom which is in common with all of them. Furthermore, the emission spectra, when smooth, generally show a depression at 3.2 μ, for which no satisfactory explanation has been found. There are no atmospheric absorption bands in this region, and fluorite is not known (see fig. 29) to have absorption bands at this point (Paschen's absorption curve for a 4 mm. plate shows an increase in absorption of 2 per cent from 2.75 to 3.2 μ, maximum at about 3.1 μ). The emission spectrum of platinum, carefully examined at the same time, showed no depression. The emission curve of the bare "heater-tube," which consists of a porcelain tube wound with fine platinum wire, likewise gave a smooth emission curve similar to that of the platinum strip. On the whole, the present data indicate that the depression is a characteristic of the oxides. In other words, the oxides have a small (sometimes large) characteristic emission band at $\lambda = 2.8$ to $\lambda = 3$ μ and a second group of bands at 4.5 to 5 μ. If this be true, then it will be necessary to assign the cause of the selective emission to the element common to all the oxides, viz, to oxygen. It is well known that groups of atoms have characteristic bands; but, heretofore, no data has been at hand which, in any way, indicated the possibility of the characteristic bands being due to a particular atom in the group.

The tentative conclusion that these emission bands in the oxides are due to oxygen atoms is perhaps to be expected, for the presence of traces of the universal impurity, silica, will not explain matters. The oxides are the most important and the most stable of all the important groups of chemical compounds; and the spectra of substances belonging to a particular group are similar. But few substances are inert to the action of oxygen. The spectrum of oxygen (see Carnegie Publication No. 35, p. 49) shows absorption bands at 3.2 and 4.75 μ. The emission spectra of CO and CO_2 show bands in the region of 2.7 and 4.75 μ (Carnegie Publication No. 35, p. 313). Oxygen in a vacuum-tube showed a strong emission band at 4.75 μ, which, at the time the research was made, was ascribed to CO or CO_2 supposed to be formed by the electrical discharge. In view of the

fact that, with rise in temperature, the CO_2 emission band shifts toward that of CO, at 4.6 μ, and that eventually all three gases, CO_2, CO, and O, when radiating by electrical excitation in a vacuum-tube, have their important emission band in common at 4.75 μ, it does not seem unreasonable to assume that the latter maximum is due to the oxygen atom set free during the time intervening between dissociation and recombination, brought about by the electrical discharge in the carbon oxides.

In a broad sense the intensity and sharpness of the emission bands are a function of the electrical conductivity. The best insulators (strong bases), *e.g.*, the refractory silicates, the oxides of aluminium, zirconium, erbium, etc., have the sharpest emission bands, while the best electrical conductors, such as the oxides of cerium, iron, zinc, etc., have no sharp emission bands. The molecular weight of the base seems to affect the sharpness of the bands to as great an extent as does the electrical conductivity, the sharpest bands occurring as a rule in oxides of low basic molecular weight. These results, if true, are to be expected from our knowledge of the emission, absorption, and reflection of electrical conductors and insulators.[1]

Paschen, using the spectral energy curves of the oxides of iron and copper, found no variation of the emissivity constant, a, with rise in temperature. On the other hand, Lummer and Pringsheim, using the total radiation from these substances, found that the emissivity increased with rise in temperature. Such a change in emissivity is to be expected, for it can be shown that at the highest temperatures the emissivity constant, a, must decrease, otherwise a point would be reached where the emissivity is greater than that of a complete radiator. In the present curves, where sometimes at high temperatures the emission seems to be distributed into apparently two bands, the "constant" a, derived from the spectral energy curve of one band, may be different from that obtained from the total radiation measurements. This is illustrated in the present study of the Nernst glower, where Mendenhall and Ingersoll,[2] using total radiation, found no certain variation in a with rise in temperature.

From one line of theoretical consideration, one might expect to find, with rise in temperature and the accompanying increase in the electrical conductivity of the oxides, that the reflecting power increases. If this be true, then the spectral emission ought to become more continuous, as is found in the Nernst glower, and the emissivity constant, a, should retain a high value similar to that of metallic electrical conductors. The value of a from the spectral radiation curve was found to decrease with rise in temperature, while Mendenhall and Ingersoll found no certain variation in a, when measuring the total radiation. It is evident that experiments

[1] This subject has been thoroughly treated by Aschkinass: Ann. der Phys. (4), 17, p. 960, 1905.

[2] Mendenhall & Ingersoll: Phys. Rev., 24, p. 230, 1907; 25, p. 1, 1907.

on the reflecting power of oxides at high temperatures will be necessary. The emissivity of the sharp spectral lines in a magnetic field will also require examination, although, on account of the wave-lengths involved, the possibility of obtaining results is not promising.

It may be added that the well-defined maxima of emission are not affected by change in temperature, which is in marked contrast with the results of Königsberger[1] for the limited region of the visible spectrum. Whether the emission maxima at 2.85 μ and 4.75 μ are due to the presence of water, in the various minerals, remains to be determined. If they are due to water, then one would expect to find them in calcium sulphate ($CaSO_4 + 2H_2O$), as well as in calcium oxide (CaO; probably some $CaOH$). But in the sulphate no band was found at 2.9 μ, where the emission should be the most intense if due to water. The band at 4.75 μ is characteristic of the sulphates (see Carnegie Publication No. 65). On the whole, the assumption that these bands are due to the presence of water is no more satisfactory than to ascribe them to the common constituent, viz, oxygen.

The isochromatics of oligoclase show that the emissivity is proportional to the energy in-put, thus differing from the other solids investigated; but, in view of the fact that in the oxyhydrogen flame the oligoclase emits an intensely white light, it appears that the emissivity must suddenly undergo a change in the visible spectrum, and perhaps form a more continuous spectrum in the infra-red.

In considering the emissivity of these oxides in connection with the radiation from the sun which is a mixture of these substances in various conditions of temperature and physical state, and remembering that the tendency of the solids is to emit a continuous spectrum at high temperatures, it forms an interesting field for speculation as to what one ought to expect for the composite radiation from the solar surface. The available data show that gases radiating in a vacuum-tube and the metallic vapors in the arc have their strongest emission lines in the region of 1 μ. In the spark discharge the metallic vapors appear to have their maximum energy in the ultra-violet. With data provided by the Astrophysical Observatory (see vol. 2 of the Annals), giving the distribution of energy in the normal solar spectrum, it has not been possible for me to compute a consistent λ_{max} for different wave-lengths, nor a uniform value of the radiation constant a (the value of a varied from 21.9 at 0.4 μ, 15.6 at 0.5 μ, 11.0 at 0.6 μ, 7.8 at 0.7 μ to 5.4 at 1.2 μ), by the methods given on a previous page, and it seems evident that these laws are not applicable. If, as the data herewith presented on the emissivity of the oxides seems to show (assuming the solar surface to be solid, electrolytic conductor as compared with a pure metal with high reflecting power) these radiation laws do not hold, how much less must they be true in the case of the solar surface in its real condition.

[1] Königsberger: Ann. der Phys. (4), 4, p. 796, 1901.

CHAPTER III.

RADIATION FROM SELECTIVELY REFLECTING BODIES, WITH SPECIAL REFERENCE TO THE MOON.

In Carnegie Publication No. 65, p. 110, on infra-red reflection spectra,[1] the writer showed that all the silicates examined have a region of strong selective reflection in the region of 8 to 10 μ and discussed the effect this would have upon a reflecting surface like the earth, or the moon, which is composed largely of silicates. Since this discussion has brought forth comments favorable and unfavorable, in print and in private communications, the purpose of the present paper is to summarize, in a general way, the present data bearing upon the subject, and to discuss certain points not mentioned in the previous communication. The computed temperatures of the sun and of the moon derived in the present paper will be used in the subsequent calculations, which will be found to be in slight disagreement with the writer's previous results. As a whole, it will be shown how easy it is to obtain estimated values which ultimately can have but little meaning other than a guide in experimental work.

THE EFFECTIVE TEMPERATURE OF THE SUN.

It has been shown by Poynting[2] that, when a surface is a complete radiator and absorber, its temperature can be determined at once by the fourth power law, if we know the rate at which it is radiating energy. If it radiates what it receives from the sun, then a knowledge of the solar constant enables us to find the temperature, which will be the highest the surface can attain when it is receiving heat only from the sun. Knowing the solar constant and the radiation constant ($\sigma = 5.32 \times 10^{-5}$ ergs Kurlbaum)[3] Poynting computes the effective temperature of the sun. If s is the radius of the sun's surface, R is the radiation per square centimeter; then the total rate of emission is $4\pi s^2 R$. This must equal the radiation passing through the sphere of radius r, at the distance of the earth, and with a surface $4\pi r^2$ gives

$$4\pi s^2 R = 4\pi r^2 S$$

where S is the solar constant. Hence $R = 46000\ S$. Using the solar

[1] Investigations of Infra-red Spectra, Parts III and IV, published by the Carnegie Institution of Washington, D. C., December, 1906.

[2] Phil. Trans. Roy. Soc. Lond., vol. 202 A, p. 525, 1903.

[3] Kurlbaum: Wied. Ann., 65, p. 748, 1898.

constant $S=2.5$ gram calories per minute $=0.175\times10^7$ ergs per square centimeter per second, $R=0.805\times10^{11}$ ergs.

If we equate the sun's radiation to $\sigma\theta^4$, where σ is the radiation constant, we get θ, the "effective temperature" of the sun, that is, the temperature of a full radiator which is emitting energy at the same rate.

Thus, $5.35\times10^{-5}\ \theta^4=0.805\times10^{11}$; whence $\theta=6200°$ abs.

With each new determination, however, the solar constant is being reduced from the former high value, so that a more probable value[1] is about 2.1 gram calories per square centimeter per minute.

Using this value of $S=2.1=0.147\times10^7$ ergs per square centimeter per second,

$$R=0.0676\times10^{11},$$

whence

$$\theta=5980° \text{ abs.}$$

This is somewhat closer to Wilson's[2] value (5773° abs.), which he obtained by making a direct comparison of the radiation from the sun with that from a "full radiator"[3] at a known temperature.

Warburg[4] has also computed the probable temperature of the sun. He assumes that the rate of radiation per degree is constant, and that the Stefan-Boltzmann law is applicable at all temperatures. For $S=2.54$ gram calories per second, the computed temperature is 6256° abs., and for $S=2.17$ gram calories per second, a temperature of 6014° abs.

Fery and Millochau[5] have measured the temperature of the solar surface with a pyrometer. The mean value of the observed temperature, after correcting for atmospheric absorption, is 5620° abs. For different parts of the solar disk the temperatures vary from 5888° to 5963° abs.

Abbot (*loc. cit.*) gives a solar spectrum energy curve, deduced from bolometric measurements, in which the maximum occurs at $0.49\,\mu$, with a possibility of the maximum[6] lying at about $\lambda=0.46\,\mu$. The equation $\lambda_{max}\,T=\text{const.}=2920$, using the value of $\lambda=0.46\,\mu$, gives a black-body

---

[1] Abbot: Smithsonian Miscellaneous Collections, vol. **45**, p. 81, 1903. See also his later results, Annals Astrophys. Obs., vol. **2**, p. 99.

[2] Wilson: Proc. Roy. Soc., vol. **69**, p. 312, 1901.

[3] Poynting (loc. cit.) very aptly says: "A surface which absorbs and therefore emits every kind of radiation, is usually described as 'black', a description which is obviously bad when the surface is luminous. It is much better described as 'a full absorber' or 'a full radiator,'" *i.e.*, a complete radiator, as distinguished from a partial radiator or so-called "non-black body." In justice to Kirchhoff who was the first to give a clear discussion of this subject, it should be called the *Kirchhoff radiator*.

[4] Warburg: Verb. Deutsch. Phys. Ges., **1**, p. 50, 1899.

[5] Fery & Millochau: C. R., **143**, pp. 505, 570, 731, 1906.

[6] The curve as drawn by Abbot is very asymmetrical and depressed on the side of the short wave-length. From the data given, it is possible to draw the radiation curve more symmetrical, as one would expect it to be, which shifts the maximum to about $0.46\,\mu$. See also his later results, Annals Astrophys. Obs., vol. **2**, which have been published since writing this paper.

temperature of about 6300° abs. One of the most refractory substances farthest removed from a full radiator in its emissive power is bright platinum. For this substance the constant is 2630 instead of 2920. If the radiation from the sun is purely thermal it must lie between the "black body" and bright platinum in its radiating properties.

If the sun radiates like platinum, from the equation

$$\lambda_{max} T = 2630, \text{ using } \lambda_{max} = 0.46\,\mu \qquad T = 5700° \text{ abs.}$$

The value of the sun's temperature, viz, 5900°, used in the present computations, is about the mean of the "observed" and the computed temperatures. From the results given in the preceding chapter, it is evident that the true temperature of the sun can not be determined by these methods.

THE LIMITING TEMPERATURE OF THE SURFACE OF THE MOON.

Poynting (*loc. cit.*) further shows that when there is no conduction inwards from the surface, the highest temperature of a full radiator is attained when its radiation is equal to the energy received. Equating the energy to the solar constant, using $S = 0.175 \times 10^7$ ergs

$$5.35 \times 10^{-5} \theta^4 = 0.175 \times 10^7$$

whence

$$\theta = 426° \text{ abs.}$$

which is the upper limit of the temperature of the moon, assuming that it absorbs all the energy received from the sun. If part of the energy is reflected and only a fraction x of that falling on it is absorbed, then the effective lunar temperature is $426\sqrt[4]{x}$ abs. From Langley's[1] estimate that the moon absorbs $x = \frac{7}{8}$ the energy it receives, Poynting (*loc. cit.*) computes the upper limit of temperature of the surface exposed to a zenith sun to be

$$\theta = 426 \times (\tfrac{7}{8})^{\frac{1}{4}} = 412° \text{ abs.}$$

But this upper limit to the temperature of the hottest part of an airless planet is never attained because the moon turns the same face to the earth instead of to the sun. He shows that, if N is the normal stream of radiation from a unit of surface of the moon immediately under the sun, the normal stream from the equivalent flat disk is $Nd = \frac{2}{3}N$.

"The effective temperature of the flat disk is therefore $\sqrt[4]{\frac{2}{3}}$ that of the surface immediately under the sun at the same distance from it. Then the effective average temperature is $412 \times \sqrt[4]{\frac{2}{3}} = 371°$ abs. The upper limit then, to the average effective temperature of the moon's disk, is just below that of boiling water."

If we use $S = 0.147 \times 10^7$ instead of 0.175×10^7, $\theta = 408°$ abs. and the "effective average temperature" is $408\sqrt[4]{\frac{2}{3} \cdot \frac{7}{8}} = 350°$ abs. or 82° C. for the full moon. This assumes no conduction inwards. Evidently there

[1] Langley: Nat. Acad. Sci., vol. 4, part. 2, p. 197.

is some heat conducted inwards, for the results of Langley (*loc. cit.*) show[1] that the surface of the full moon is about 300° abs.

FALL OF TEMPERATURE OF THE MOON DURING ECLIPSE.

As already mentioned in Carnegie Publication No. 65, page 110, Langley made observations on the eclipse of the sun on September 23, 1885, which indicate a sudden and very rapid fall of energy received from the moon at the beginning of the eclipse, with some indications of a rise nearly as rapid after its conclusion. In Carnegie Publication No. 65, page 113, are plotted his observed galvanometer deflections during the progress of the eclipse. The observations were interrupted by the formation of clouds just at the predicted time for the moon to leave the umbra. The curve shows that in the short time of about 1.5 hours, in passing from the penumbra to the umbra, the radiation from the west limb has fallen from a maximum to a zero value. In other words, the fall of temperature is practically coincident with the change in illumination, and at first appeared to the writer[2] to indicate that the greater part of the observed energy is due to reflection. That the moon at mid-eclipse is still as warm as the earth is shown by the fact that the galvanometer gave zero (or only small positive) deflections. If the moon had been cooler than the earth, then the deflections would have been negative. Subsequent search of the literature on the subject shows that Very[3] found appreciable radiation from the moon during totality. The following computations show that this is to be expected. After about 11 days of insolation the temperature of the sun-lit surface of the moon will be fairly constant. From the surface inwards there will be a layer which may be considered at a uniform temperature for the period of 1.5 hours, as compared with 11 days. If, then, the moon were suddenly eclipsed, the fall of temperature of the surface with time ($x=0$, $\theta=f(t)$; assuming at time $t=0$, that $\theta_0=300°$ abs.) is found from the equation

$$k\frac{d^2\theta}{dx^2}-\sigma\theta^4=ds\frac{d\theta}{dt}$$

where k=conductivity, d=density, and s=specific heat. The first term in the equation represents the energy lost by conduction (it is assumed

---

[1] Very, Astrophys. Jour., **8**, pp. 273 and 274, 1898, however, records "inferred effective temperatures" as high as 455° abs. for limited regions of the moon, and (loc. cit., p. 286) a mean surface temperature of +97° C. The fact that the moon absorbs energy from the sun (the maximum of which is of short wave-lengths) and emits energy of wave-lengths from 8 to 10 μ, where, on account of the probable high reflecting power, the emissivity is very low, would explain why Mr. Very has found a temperature which is much higher than that of a complete radiator under similar conditions.

[2] Phys. Rev., 23, p. 247, 1906.

[3] Very: Prize Essay on the Distribution of the Moon's Heat, p. 40. Professor Very has called my attention to an error in Carnegie Publication No. 65, p. 112, third line from the top: viz, "Harrison (not Langley) reminds the reader . . ."

that there is conduction in only one direction, hence the differential terms in y and z disappear). The second term represents the loss of heat by radiation from the surface; while the last term represents the change in temperature at the surface. The dependent variable enters here as a fourth power, and makes the solution difficult. The computations are made for instantaneous eclipse, while in the actual case the shadow moves slowly across the surafce. Hence the error due to neglecting conductivity is partly compensated by the slow eclipse.

By neglecting conductivity from the interior, the temperature of the surface will fall more rapidly and we have a steeper temperature decadence curve. The solution of the equation is very simple if we neglect conduction, and is

$$\theta = \frac{\theta_0}{\sqrt[3]{\frac{3\theta_0^3\sigma t}{ds}+1}}$$

for t in minutes, $\sigma=76.6\times10^{-12}$ gram calories per square centimeter per minute, $d=2$, and $s=0.2$ (approximate values for rock material). Hence

$$\theta = \frac{300°}{\sqrt[3]{1+0.0155t}}$$

In fig. 97 are plotted the temperature decadence curves for the radiation constant σ, for 0.3 σ (emissivity of iron oxide) and for 0.1 σ. The curves show that for a full radiator the temperature would fall from 300° to 280° (room temperature when the bolometer would be in temperature equilibrium with the moon) in 17 minutes, for 0.3 σ in 55 minutes, and for 0.1 σ in 140 minutes. The solution for 0.1 σ and 0.3 σ is, of course, only approximate since the emissivity varies more nearly as the fifth power instead of the fourth power, as here used; and the computed temperatures should be somewhat higher. The computation is also made (fig. 97), assuming the temperature to be 350°. Here, for a complete radiator the temperature would fall from 350° to 280° in 38 minutes, and for 0.3 σ in about 130 minutes. By including the conductivity term these periods would be considerably prolonged. The present solution is close enough, however, to show that the temperature (300°) decadence curve is not coincident with the eclipse curve, unless the emissivity is of the order 0.3 σ. Hence the writer's[1] previous surmise that at the beginning of totality radiation should still be appreciable is substantiated, although the observations made by Langley seemed to contradict it. Very's observations[2] show that during totality of the eclipse of January 17, 1889, the radiation from the umbra of the eclipsed moon was about 1 per cent of the heat which was to be

[1] Phys. Rev., 23, p. 247, 1906.
[2] Very: Distribution of the Moon's Heat, p. 40.

expected from the full moon. Boeddicker[1] also records that the minimum of the heat-effect falls decidedly later than the minimum illumination.

REFLECTION AND RADIATION FROM THE MOON.

Using the data just computed, we are now in a position to make a rough comparison of the relative amounts of energy reflected by and radiated from the moon. In the short wave-lengths the reflecting power depends upon the refractive index, while at 8 to 10 μ the reflecting power will depend upon the refractive index and the extinction coefficient (see Drude's Optics, p. 336), and at all times will have a high value, except at 7 μ. The reflecting power of the moon is variously recorded[2] from 0.09 to 0.23, which values are several times higher than the refractive index of ordinary rocks permits. This seems to indicate internal reflection.

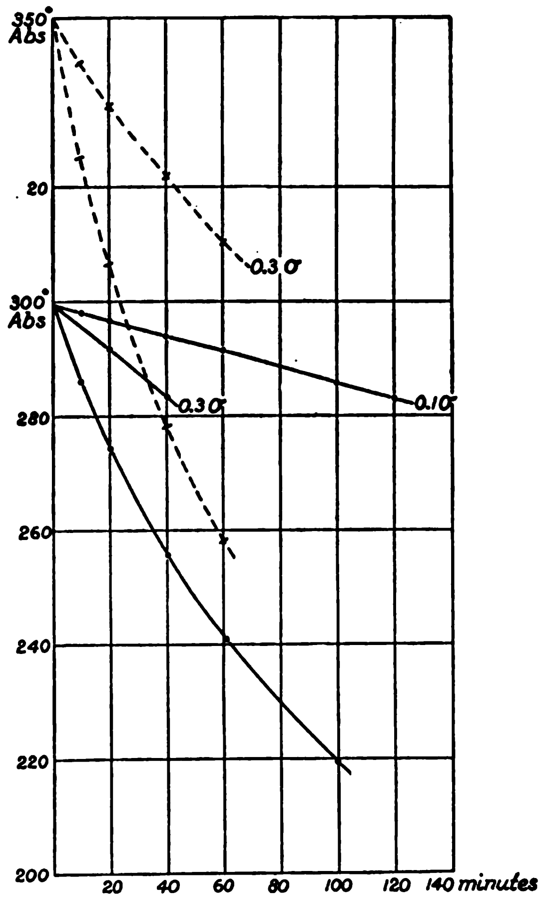


FIG. 97. — Lunar temperature decadence during eclipse.

The question is therefore reduced to finding the ratio of the energy emitted by the moon to the energy of the sun, reflected from the lunar surface. For this purpose the temperatures of the moon and of the sun (350° abs. and 5900° abs., respectively) given on the preceding pages are employed. The values are taken slightly lower, although it makes but slight difference in the final computation. We are not so much concerned with the question as to where the maximum emission of the moon occurs as we are in the fact that, in the region of 8 to 10 μ, where Langley observed radiation from the moon, there is also reflected energy from the sun. From the transmis-

[1] Boeddicker: Trans. Roy. Dublin Soc., 3, p. 321, 1885.
[2] Very: Astrophysical Jour., 8, p. 276, etc., 1898.

sion curves of the water vapor (curve c, fig. 102) it will be seen that in the region from 5 to 8 μ nearly all the energy will be absorbed by the earth's atmosphere. The reflecting power of the moon for visible rays, according to Langley (*loc. cit.*), is only $\frac{1}{500000}$ full sunlight. Assuming that at 9 μ the reflecting power of the silicates is, on an average, 10 times that at 0.5 to 4 μ, this value becomes $\frac{1}{50000}$ or 0.00002. (This seems a fair estimate of ratio of the reflecting power of the silicates at 1 and 9 μ. In the absence of better data this solution can be only a rough approximation.)

Using the above values for the temperature of the moon and of the sun, from Planck's[1] formula for the distribution of the energy in the spectrum of a complete radiator (which, of course, the moon is not)

$$E_\lambda = c_1 \lambda^{-5} (e^{c_2/\lambda T} - 1)^{-1}$$

we can obtain the ratio of the intensities for the two temperatures $T = 350°$ abs. and $T_2 = 5900°$ abs. from the formula

$$(e^{c_2/\lambda T_2} - 1) \div (e^{c_2/\lambda T_1} - 1)$$

Where $c_2 = 14{,}500$ and $\lambda = 9\ \mu$. The ratio is 0.00316. But the moon, not being a perfect radiator, will have a smaller emissivity at 8 to 10 μ. If its surface were iron oxide,[2] its emissivity would be only 0.3 that of a full radiator, and, for the region at 9 μ, judging from the drop in the emission curve (see Carnegie Publication No. 65, p. 111) and the high reflecting power of the silicates, the emissive power may be less than this, say 0.1. This ratio of the emissive power of the moon to that of the sun will then be 0.000316, which is 16 times (0.000316 ÷ 0.00002) the reflected energy of the sun from the moon. If we had taken 300° as the temperature of the moon, then this ratio would be (0.00014 ÷ 0.00002) = 7 instead of 16. Computations[3] like these, which require all sorts of assumptions, can be of little value ultimately. Any computation can not be more than a rough approximation, for the reflecting powers, observed up to 4 μ, will be too high, due to internal reflection. In the region of 8 to 10 μ (for silicates) there can be but little if any internal reflection. Hence, the ratios just obtained are too low, but how much so is difficult to estimate because of the lack of data. We know that Langley observed also direct radiation from the sun, in this region of the spectrum, and from existing data of the radiation from the moon in this region we do not know how much of it is selectively reflected energy from the sun. The amount reflected must be small, but, since the total amount emitted is also small, it is important to establish the fact that there is selective reflection in this region.

---

[1] Planck: Verb. Deutsch. Phys. Ges., 2, p. 202, 1900.

[2] Kayser: Spectroscopy, vol. 2, p. 80.

[3] Very: Astrophys. Jour., 24, p. 353, 1906, computes a much greater difference between the amount reflected and the amount emitted.

EMISSION FROM A PARTIAL RADIATOR.

We have now to consider a problem which has heretofore not been discussed in connection with the radiation from the moon. Planck's formula for the intensity of radiation at a given wave-length λ in the spectrum of a complete radiator is

$$E_\lambda = c_1\lambda^{-5}(e^{c_2/\lambda T} - 1)^{-1}$$

For any radiating body the emission $\phi_\lambda = A_\lambda E_\lambda$, where A is the absorption coefficient. But $A_\lambda = 1 - R_\lambda$ (for "transparent media," *i.e.*, non-metals), where R is the reflecting power, and hence $\phi_\lambda = E_\lambda\,(1 - R_\lambda)$.

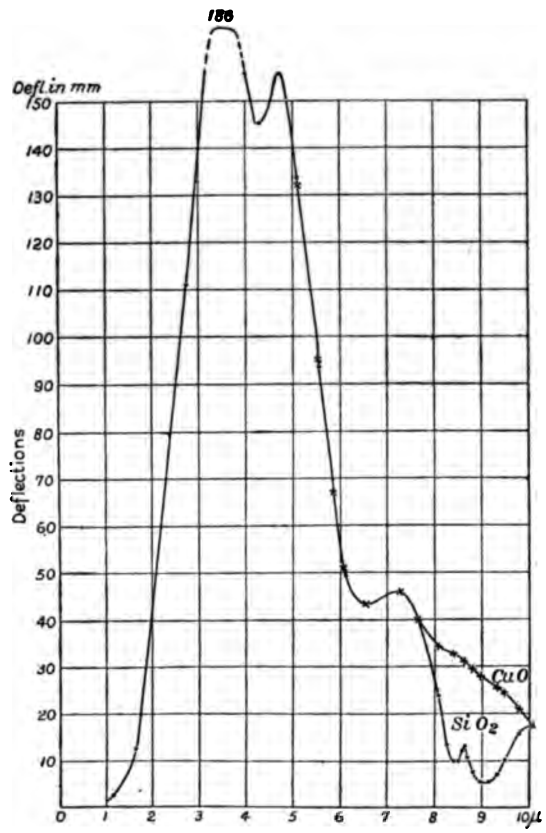


FIG. 98. — Emission spectrum of copper oxide and of quartz, 325° C. (Rosenthal).

It follows therefore that a selectively reflecting body like quartz will be a partial radiator[1] and that if we compare its radiation curves with that of a complete radiator, there will be *minima* of *emission* in the region

[1] Partial radiators may be divided into so-called "gray bodies" and bodies having a highly selective emission. Quartz belongs to the latter class.

of 8.5 and 9.03 μ. This was predicted by Aschkinass[1] and experimentally verified by Rosenthal,[2] with quartz, mica, and glass (see fig. 98). The latter found the observed emission curves of these substances to coincide precisely with the computed curves, using the observed reflecting power of these minerals and the observed emission curve of a full radiator at the same temperature.

Since we have constantly before us examples of selective emission, such as the Welsbach mantle, and high temperature radiation of such metals as tungsten and tantalum, in the visible spectrum, it will be of interest to consider the radiation of several substances having bands of selective reflection in the infra-red. In fig. 99 is given an illustration of the marked effect of selective reflection upon emission. The extraordinary reflection of carborundum (SiC) has been found in only one other substance, viz,

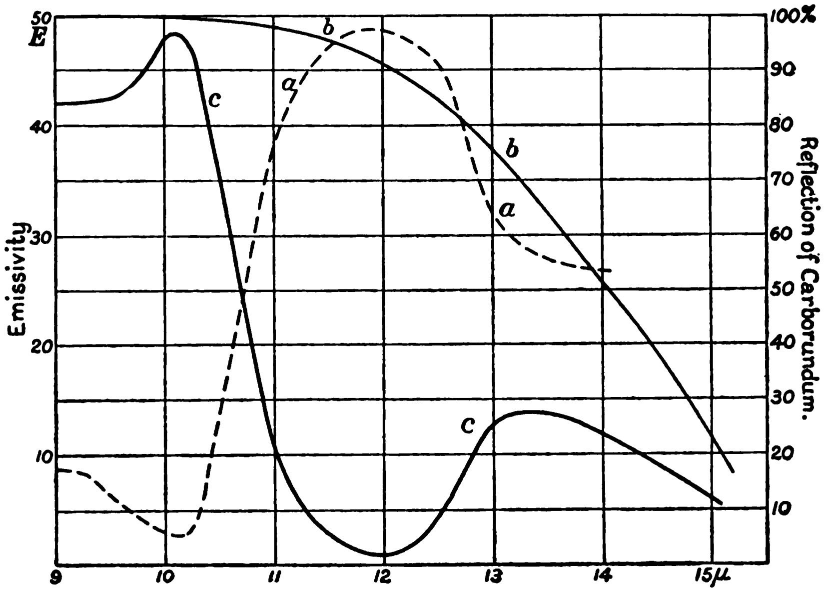


FIG. 99. — Reflection from carborundum (*a*); Radiation of complete radiator at 300° abs. (*b*); Radiation from carborundum at 300° abs. (*c*).

quartz, and in the latter it is the result of two well-defined bands, at 8.5 and 9.03 μ. The effect of such a band on the dispersion of this substance must be very marked. In fact, the unusual dispersion in the visible spectrum found by others no doubt is greatly influenced by this band. In this figure are given the computed energy curve for a perfect radiator (using Planck's formula — any temperature might have been selected instead of 300° abs.) and the computed energy curve of carborundum at the same

[1] Aschkinass: Verb. d. Deutsch. Phys. Ges., **17**, p. 101, 1898.
[2] Rosenthal: Ann. der Phys. (3), **68**, p. 791, 1899.

temperature, using the formula $\phi_\lambda = E_\lambda(1 - R_\lambda)$, where R is the observed reflecting power and E is the corresponding intensity of the full radiator. It will be noticed that the radiation will be highly selective, and that at 10 μ it approaches closely to that of the complete radiator. If, then, one were to observe the emission curve of carborundum, the maximum at 10 μ would appear as an "emission band," but its explanation is different from that of emission bands of hot vapors, *e.g.*, CO_2 and H_2O in the Bunsen flame. In fig. 100 is given the observed reflection curve, *a*, of quartz, and the computed emission curves of a complete radiator, *b*, and of quartz, *c*, at a temperature of 400° abs.

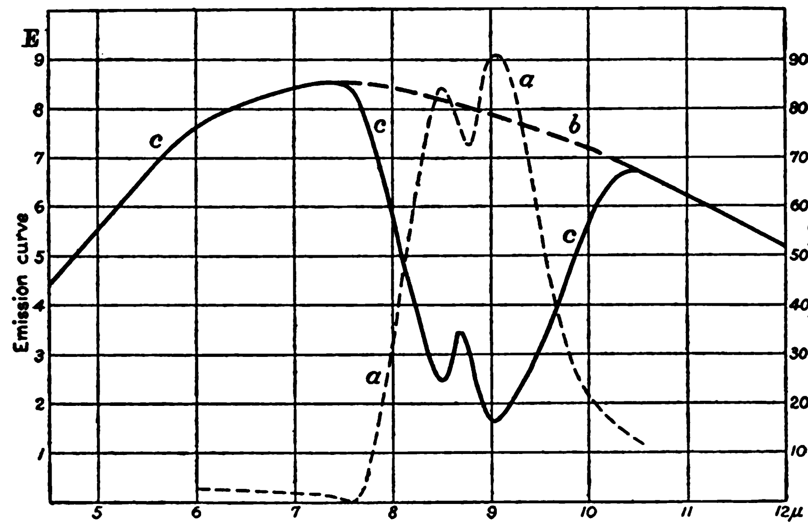


FIG. 100. — Reflecting power of quartz (*a*); Emission of complete radiator at 400° abs. (*b*); Emission curve (*c*) of quartz at 400° abs.

In fig. 101 are given the computed emission curves, *a* and *b*, for a complete radiator, for temperatures 300° and 400° abs., respectively, and the corresponding emission curves, *c* and *d*, of quartz, at the same temperature using the values of the reflecting power of quartz given by Rosenthal (*loc. cit.*). These values are somewhat lower than found by the writer. In general, the difference in the emissivity of the silicates and that of a full radiator at 8 to 10 μ would not be so marked as in quartz. For mica (see Carnegie Publication No. 65) the emission minima would occur at 9.1 and 9.8 μ, while for granite the emission minimum would extend from 8.5 to 10 μ. The combination would have an appreciable effect upon the radiation curve of a surface like that of the moon. Even, if we exclude atmospheric absorption, the emission curve (*a*, fig. 102) will not be smooth and continuous, as some writers seem to think. If we superpose atmospheric absorption, the emission curve of quartz (curve *c*, fig. 101) will be somewhat as shown in curve *b*, fig. 102. Transmission curve *c* (fig. 102) is

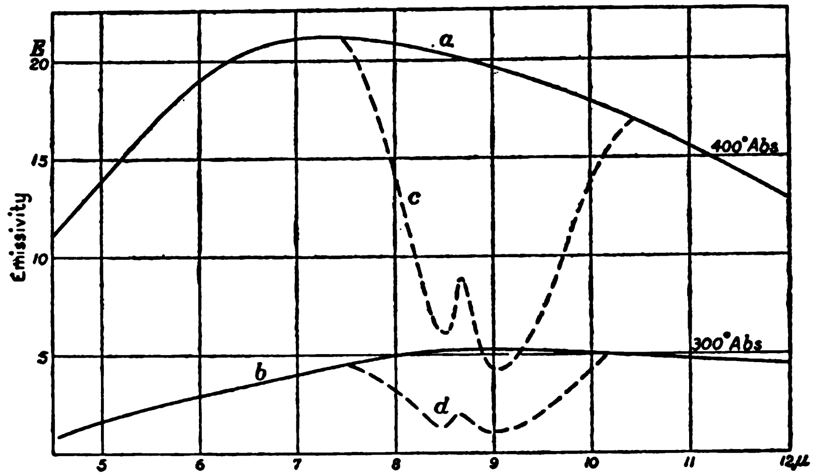


FIG. 101. — Emission of complete radiator (a) and (b); Emission of quartz (computed).

for a column of air 110 meters in length, containing 1.2 mm. precipitable water,[1] and is due to Langley (*loc. cit.*). A thick layer would shift the maximum at 8 μ toward 8.3 μ found in the moon's radiation curve. In fig. 103, curves *a*, *c*, and *d* show some of Langley's observed lunar radia-

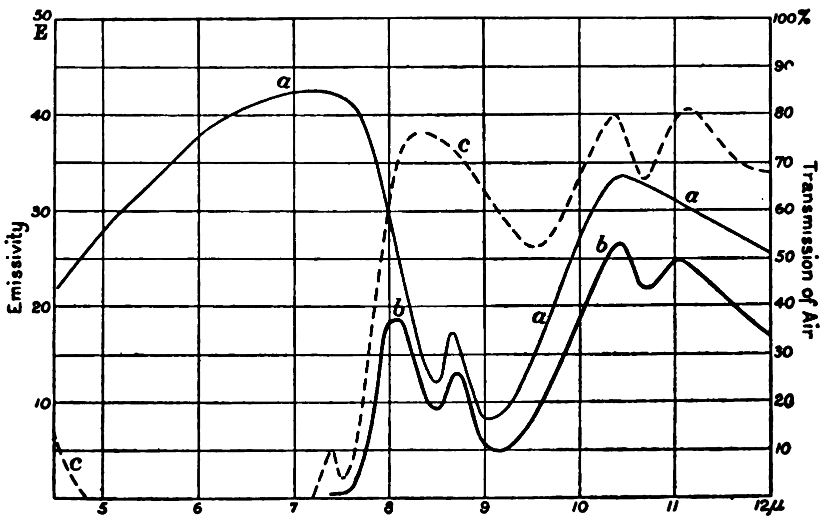


FIG. 102. — Emission of quartz (curves *a* and *b*); transmission of air (Langley).

tion curves, and as a whole there is a close parallelism between the theoretical curve *b*, from fig. 102, and the observed curves, at 10.7 μ, where we have to consider only atmospheric absorption. From 8 to 9 μ, however,

[1] Apparently water-vapor is more transparent than a film of the liquid, for a film of even one-tenth this thickness is opaque to heat rays beyond 5 μ.

we have to consider the combined effect of atmospheric absorption, of incomplete emission of the moon (emission minima from 8.5 to 9.8 μ), and of selectively reflected energy from the sun. The latter will, no doubt, vary the most in intensity. The computed emission curve is the most intense at 10.2 μ, while the observed is the most intense at 8.3 μ (see fig. 103). This is to be expected if the observed energy curve is the composite of the selectively emitted energy of the moon, and the selectively reflected energy of the sun, which is selectively transmitted by the earth's atmosphere. The selectively reflected energy of the sun would to a certain extent fill up the minima in the lunar emission curve, thus making it higher at 8.3 μ than at 10.2 μ, and, as far as our present knowledge goes, would explain the observed curves *a*, *c*, *d*, fig. 103, which lack a minimum at 8.5 μ. As

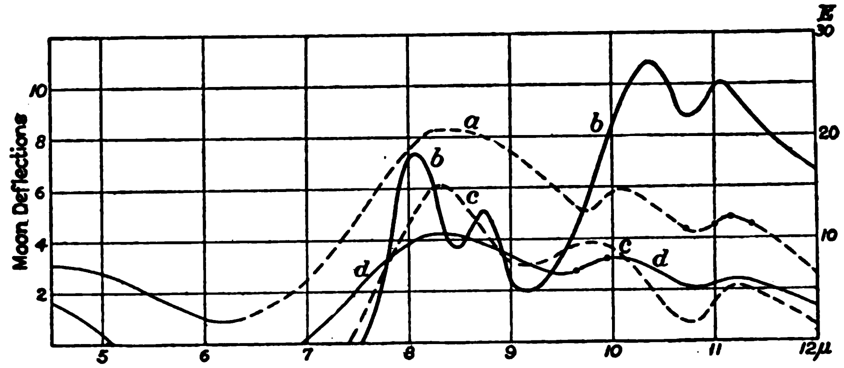


FIG. 103.—Emission of quartz (*b*); Emission from moon (Langley).

a whole, from whatever standpoint we view this matter we come to the same conclusion, viz, that in the region from 8 to 10 μ the energy emitted from the moon consists of its own proper radiation and of reflected energy from the sun.

To sum up, we know that Langley observed radiation from the moon in the region of 8 to 10 μ. He observed also direct radiation from the sun in this same region; but we do not know how much of this is superposed upon the direct radiation from the moon due to the latter being selectively reflecting in this region of the spectrum. As stated in Carnegie Publication No. 65, page 115, computations which require all sorts of assumptions will not settle the question. Bolometric comparison of the spectrum energy curves of the sun and of the moon made at high altitudes will be of greater service in clearing up the matter. Very's[1] suggestion of searching for a solar image in the lunar image, with a delicate heat-measuring instrument covered by a screen with a pin-hole aperture, also deserves a thorough trial. Exception has been taken to the writer's statement (*loc. cit.*) that, of the radiation observed by Langley in the lunar spectrum at

[1] Very: Astrophys. Jour., 24, p. 353, 1906.

8 to 10 μ, we do not know how much is selectively reflected energy from the sun. But the writer maintains that just as soon as we admit the possibility of the moon being selectively reflecting in the region where it has its own proper radiation, then the use of glass[1] as an absorbing screen for testing the quality of that radiation is inadmissible, although it does serve as a rough test of the reflected energy at 0.5 to 3 μ. For this purpose it has been serviceable, and when we consider the great difficulties under which such work must be carried on, and the numerous corrections that must be introduced (which at all times may be larger than the one for selective reflection), the use of a glass screen is not objectionable.

Furthermore, we have noticed that the silicates reflect as a transparent medium in all regions of the spectrum considered, except from 8 to 10 μ, where it reflects like a metal. This means that the reflected energy in all these regions except 8 to 10 μ will consist of two parts, viz, that reflected from the outer surface and that due to internal reflection. From 8 to 10 μ there will be but little, if any, energy due to internal reflection. Hence, to use the reflected energy spectrum of the moon from 0.5 to 4 μ as a means of estimating the amount of reflected energy at 8 to 10 μ is not a fair test, and, as used (for want of better data) in the present paper, can only serve as an approximation. As in the case of emission spectra, it ought to be possible to analyze a substance by means of its reflection bands. The constitution of an isolated body like the moon, shining by reflected light, might thus be determined. This will probably never be possible since terrestrial atmospheric absorption will interfere with the observations, while a far greater sensitiveness in the radiometers will have to be attained than now is possible.

From whatever standpoint we view the matter, the conclusion is that the lunar surface must be diffusively, selectively reflecting, however small. Hence, in the stream of energy reflected in any direction from the lunar surface the density will be greatest for the wave-lengths of the bands of selective reflection. One would, therefore, expect to detect this difference in all directions, and not simply at the angle of reflection as suggested by Very (*loc. cit.*). It is difficult to apply a thorough test which will determine whether, and how much of, the energy from the moon is due to emission, and how much is due to reflection of energy from the sun. A rigid comparison of the energy curves of the sun and the moon in this region would be of great value. The polarization of the radiation from the moon might also be of use in deciding this point. Pfund[2] has shown that

---

[1] Various observers have compared the total radiation from the moon to that part which is transmitted by glass. Glass being opaque beyond 4 μ was assumed to absorb the proper radiation from the moon, while the part transmitted by glass was considered to be reflected energy from the sun. Evidently if there is selectively reflected energy of the sun beyond 4 μ, then it will be superposed upon the direct radiation of the moon, and the use of a glass screen for testing the lunar radiation is inadmissible.

[2] Pfund: Astrophys. Jour., **24**, p. 19, 1906.

the bands of residual rays reflected from calcite are elliptically polarized. Pflüger[1] studied the polarized radiation from tourmaline heated to high temperature. Further than this, nothing is known concerning the polarization of the radiation emitted by substances like the silicates; hence this test might not be very decisive.

To subject the above conclusions to experiment in which the reflection of a rough surface is to be measured will be accompanied with difficulties because of the smallness of the surfaces that can be used.[2] In the case of the moon an image of the whole, or a greater part of the surface, may be projected upon the spectrometer slit. This means concentrating radiation which comes from a surface many miles in diameter, as compared with a surface which, when produced in the laboratory, amounts to only a few square centimeters.

[1] Pflüger: Ann. der Phys., 7, p. 800, 1902.

[2] Since writing this, Dr. A. Trowbridge, at the Washington meeting of the American Physical Society, April 24–25, 1908, described a series of experiments on the diffuse reflection of infra-red energy, in which he showed that powdered quartz has minima of diffuse reflection in the regions where there are absorption bands (*e. g.*, 2.95 μ), and reflection maxima at 8 to 9 μ, just as obtains for plane surfaces. This is an excellent illustration of the difference of what corresponds to body color and surface color in the visible spectrum (see Wood's Optics, p. 352). It also illustrates the question of diffuse selective reflection discussed on a previous page.

APPENDIX I.

THE EFFECT OF THE SURROUNDING MEDIUM UPON THE EMISSIVITY OF A SUBSTANCE.

In most of the problems in radiation from substances the surrounding medium is air, and no account is taken of the refractive index, which is taken as unity. In a remarkable research on "The Formation of River Ice with Special Reference to Anchor Ice and Frazil," by H. C. Barnes, it is shown that the surrounding medium plays an important part in the rate of cooling of the earth's crust.

In Canada, as well as other localities having high latitudes, three kinds of ice are observed, viz, sheet or surface ice, frazil ice, and anchor ice.

Surface ice is found only in still water, and is caused by the loss of heat to the cooler atmosphere, by radiation and conduction from its surface. Thickening of the ice-sheet takes place downwards by conduction of heat through the ice to the air.

Frazil ice is the French-Canadian term for fine spicular ice, from the French for forge-cinders, which it is supposed to resemble. It is found in all rivers or streams flowing too swiftly for the formation of surface ice. A dull, stormy day, with the wind blowing against the current, is productive of the greatest amount of frazil ice, which, like anchor ice, has a tendency to sink upon the slightest provocation, and to follow submerged channels until it reaches a quiet bay. Here it rises to the under side of the surface ice, to which it freezes, forming a spongy growth, attaining great thickness; in some cases the author observed a depth of 80 feet of frazil ice.

Anchor ice, as the name implies, is found attached or anchored to the bottom of a river or stream, and often attains a thickness of 5 to 6 feet. It is also called ground-ice, bottom-ice, and ground-gru. In a shallow, smooth-flowing river we are more likely to have anchor ice formed in excess, whereas in a deep and turbulent stream we are likely to have more frazil. In a river 30 to 40 feet deep anchor ice is almost unknown, although large quantities of frazil are met with.

Barnes remarks that —

> The various facts of common observation in connection with anchor ice points to radiation as the primal cause. Thus it is found that a bridge or cover prevents the formation of anchor ice underneath. Such a cover would act as a check to radiation, and reflect the heat-waves back again to the bottom. Anchor ice rarely forms under a layer of surface ice covered with snow. It forms on dark rocks more readily than on light ones, which is in accord with

what is known in regard to the more copious radiation of heat from dark surfaces. Anchor ice never forms under a cloudy sky either by day or by night, no matter how severe the weather, but it forms very rapidly under a clear sky at night. Anchor ice is readily melted off under a bright sun. It seems highly probable, then, that radiation of heat supplies the necessary cooling to the bottom of a river to form the first layers of ice, after which the growth or building up of the ice is aided by the entangling and freezing of frazil crystals, which are always present in the water.

The author found that during rapid ice formation the water becomes slightly undercooled to the order of a few thousandths of a degree, and that the ice which is found is in a very adhesive state. On the cessation of cold weather the temperature of the water rises slightly above the freezing-point and the ice gradually melts. Anchor ice rises from the bottom in mild weather and also in extreme cold weather under the influence of a bright sun, when it is dangerous to small boats. It is also known to lift and transport large boulders. On the other hand, a bright sun prevents the water from becoming undercooled and the formation of frazil ice. The author's conclusion that anchor ice is formed by radiation rather than by conduction is practically the same as that of Farquharson in 1841.

At the request of the editor of the Monthly Weather Review, the writer[1] has inquired into the aforesaid conclusions, which at first seemed untenable. After considering various experimental data, it appears to the present writer that the explanation of Farquharson and of Barnes accounts for the observed phenomena better than any of the other theories propounded. Thus the loosening of the anchor ice under a bright sun is simple enough from the fact that water is transparent to heat-waves up to 1 μ. The thickness of the layer of ice that must be melted in order to overcome the adhesion to the rock surface must be of molecular dimensions. In addition to this, there is the tension on the rock surface due to the buoyancy of the ice, which also tends to melt the ice. The explanation of the formation of anchor ice is more difficult, and the author's statement that "it is not to be supposed, because a substance like water has been found to be highly opaque to the radiation from hot bodies, that it will be the same for cold body radiation" is a little startling, and not very clear, for the transmissivity of any region of the spectrum is independent of the temperature of the source. However, if total radiation is meant, then such an interpretation is possible. In "Investigations of Infra-red Spectra" (Carnegie Publication No. 35), several examples, *e.g.*, methyl iodide, are given, illustrating the latter case. There is no evidence, however, for saying that "it is probable that water possesses an absorption band for shorter heat-waves, but may become perfectly transparent for the longer heat-waves." It is known that water is exceedingly opaque to heat rays from 4 to 8 μ followed by a more transparent region from 8 to 20 μ (this

[1] The Monthly Weather Review, p. 225, May, 1907.

was found by Rubens and Aschkinass[1] for water-vapor, which behaves like the liquid in its properties for absorbing heat-rays), beyond which there is great opacity. In fig. 104 is given the transmission curve of a column of 75 cm. of water-vapor (due to Rubens and Aschkinass, *loc. cit.*), from which it will be noticed that there is a quite transparent region from 8 to 15 μ. They found that the heat waves at 51 μ were entirely absorbed, while at 80 μ theory (see Drude, Optik, p. 359) predicts a band of metallic reflection. Moreover, water differs from most other substances in that its great opacity is due to numerous *small* absorption bands. Consequently its absorption coefficient is smaller than that of a substance like quartz which has bands of metallic reflection at 8.5, 9.02, and 20.75 μ. Hence, there is no objection to saying that "the whole question of the formation

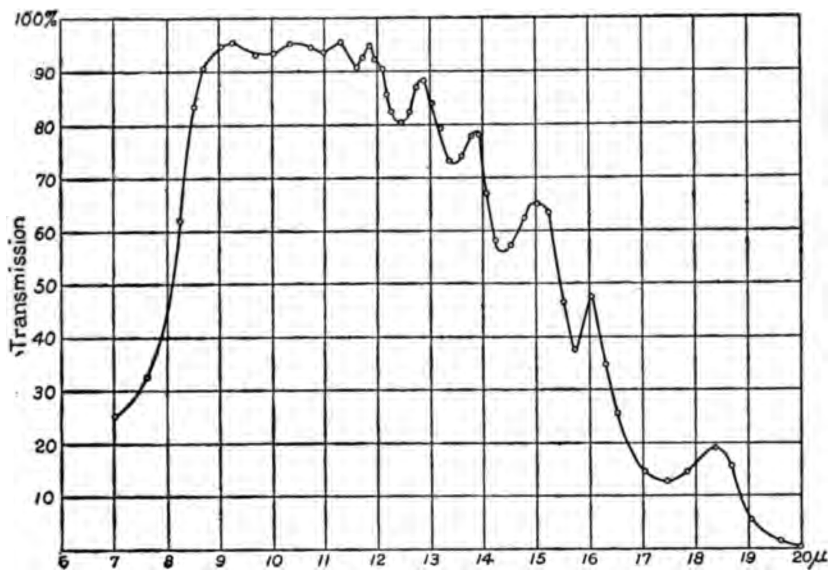


FIG. 104. — Transmission of water vapor.

of anchor ice depends upon admitting that the long heat-waves can penetrate freely through the water," for the maximum radiation of a body at a temperature of 0° C. lies in the region of the spectrum extending from wave-lengths 8 to 20 μ, and it is here that water has its greatest transparency for long heat-waves.

It is difficult to conceive of a more complex form of radiation than the one here involved. According to Provost's theory of exchanges, when two bodies are at different temperatures the hotter receives energy from, and imparts energy to, the colder by radiation, and vice versa. In the case of the river, when the sky is clear, the water is radiating into space which is

[1] Rubens & Aschkinass: Ann. der Phys. (3), 64, p. 584, 1898; also Ann. der Phys., 65, p. 251, 1898.

probably at absolute zero of temperature. The river-bed is radiating energy into the water, and probably through it into space. Leaving out of consideration the special nature of the emissivity of the two bodies (water and river-bed), it has been established (see Drude's Optics, p. 462) that the radiation from a "non-black body" is approximately proportional to the square of the refractive index of the surrounding medium, which is transparent, so that, from this standpoint, the emissivity of the river-bed into the water would be greater than that of the water into the air. Of course, if water were perfectly transparent, its emissivity would be *nil*, and the problem would be less complex. Little is known concerning the special nature of these two bodies, but from the fact that the anchor ice separates so easily from the river-bed under a bright sun, it is evident that the absorption coefficient of rock material is greater than that of water, and hence, that its emissivity must also be greater. Hence, more energy will be radiated from the river-bottom than from the water, into space, the river-bottom will become the cooler, and finally a film of ice is formed on it. During cloudy weather the temperature of the water-vapor in the air is equal to or higher than that of the water and the river-bottom. There is then an equality in the radiation, or an excess is being emitted from the clouds to the earth. A certain amount will also be returned from the clouds by reflection. Hence, the excess of radiation is toward the earth, and since the temperature of the clouds is above the freezing-point no anchor ice is formed.

To sum up, from this elaboration of the author's explanation, just quoted, of the formation of anchor ice, it will be seen that it is not only possible, but also highly probable that the cause is to be attributed to the greater emissivity of the substances forming the bed of the river, and to the greater transparency of water to heat-waves than is generally supposed to obtain for that substance. It is difficult to conceive that such a condition can exist, but the magnitude of the heat transfer, required to bring about this ice formation, must be exceedingly small, and the explanation given accounts for all of the facts observed.

On a previous page the conclusion was reached that the energy received from the moon will be the composite of the selectively reflected energy of the sun and of the selectively emitted energy of the moon, which is selectively transmitted by the earth's atmosphere. In the same manner the earth would emit selectively in the region of 8 to 10 μ and less than a complete radiator at the same temperature. It is, therefore, hotter than a complete radiator which emits the same amount of energy. All these questions are of extreme importance to the meteorologist who is concerned with the cooling of the earth. It may be added, however, in conclusion that the loss of radiation from the earth under the above conditions must be exceedingly small. In the same manner the suppression and conservation of energy in the region of 8 to 10 μ must be very small, so that it is a

matter of speculation whether the earth would be at a much lower temperature if its surface were composed of material not having bands of selective emission.

Rubens and Aschkinass (*loc. cit.*) found that after four reflections from fluorite surfaces the deflection due to solar energy is reduced to zero, showing that the opacity of the combined solar and terrestrial envelope is practically total for wave-lengths 24 to 32 μ. In a recent communication on the absence of very long waves from the sun's spectrum, Nichols[1] found that the atmospheric transmission for wave-lengths $\lambda = 51\ \mu$ can not be greater than 3 per cent. This, however, does not indicate that the sun is lacking in radiation of wave-lengths $\lambda = 51\ \mu$, as the title of the paper appears to imply, but that, whatever the intensity of the radiation emitted at 51 μ, it is almost entirely absorbed by the earth's atmosphere.

[1] E. F. Nichols: Astrophys. Jour., 26, p. 46, 1907.

APPENDIX II.

INSTRUMENTS AND METHODS USED IN RADIOMETRY.

There are few fields of experimental investigation so beset with difficulties as the quantitative measurement of radiant energy. This is due to the fact that the radiation to be measured is generally from a surface of which it is practically impossible to determine the temperature. The measurement of radiant energy usually involves its transformation into some other form, and the receiver used for this purpose is subject to losses by heat conduction within, and by reflection, radiation, and convection losses from its surface.

As a result of inquiry into the development of the various instruments and methods used in measuring radiant energy, viz, the radiometer, the thermopile, the radiomicrometer, and the bolometer with its auxiliary galvanometer, the writer has accumulated extensive data, part of which is included here, with the hope that it may be useful to others interested in the subject.

Various instruments have been devised, the sensibility, or the possible chances for improvement, of which can be rated without further investigation. That in many cases the sensitiveness has been overestimated, will be noticed in the present paper. However, four instruments, viz, the radiomicrometer, the thermopile, the bolometer, and the radiometer, have been used extensively in radiation work, and in each case the inventor has found qualities which seemed to him to render his instrument superior to other types. But, to the writer's knowledge in no instance have all four instruments been studied by any one person; and, perhaps, it should not be expected. Each instrument requires a special mode of handling, and has peculiarities which can be learned and controlled only after prolonged use. This is particularly true of the radiometer and of the bolometer with its auxiliary galvanometer.

Having already had considerable experience with radiometers, one of which was the most sensitive yet constructed, the writer has, in this examination, devoted most of his attention to the bolometer. The investigation originated for the most part from the question whether the radiometer was selective in its action, in the region of the short wave-lengths. In previous work it was found[1] that the radiometer gave small deflections in the violet spectrum of the arc where Snow,[2] using a bolometer, found large deflections.

---

[1] See Investigations of Infra-red Spectra. Part II. Infra-red emission spectra. (Carnegie Publication No. 35.)

[2] Snow: Physical Review, 1, p. 32, 1893.

In the course of the discussion it will be noticed, as was previously shown in a general way, that each instrument has some quality which makes it useful for a certain kind of work. For measuring very narrow emission lines and determining dispersion curves the bolometer is no doubt the best adapted. For measurements requiring a larger receiving surface, the linear thermopile is the more sensitive and the more precise. It has the further advantage that there is no permanent current. On the contrary, the bolometer has a current which heats the bolometer strip above the temperature of the surrounding air. This causes air currents which make the zero unstable. This is not true of the thermopile. Less is known concerning the radiometer, which rivals the bolometer and the thermopile in sensitiveness. Furthermore, the radiometer is not subject to magnetic perturbations. Its window limits its usefulness to the region of the spectrum up to 20 μ. The fact that it is not portable is a very minor objection.

I. THE MICRORADIOMETER.

Since we are concerned with radiation meters of the greatest sensitiveness, the ingenious device of Weber,[1] called the microradiometer, deserves passing notice. The instrument is not unlike a combination of a differential air thermometer and Wheatstone bridge. Two arms of the bridge consist of a thin glass tube containing a bit of mercury at the center with a solution of zinc sulphate at the ends, into which dip platinum electrodes. The ends of the bulbs are covered with rock-salt windows. If radiant energy is allowed to enter one of these bulbs, the air expands and pushes the liquids toward the opposite bulb. This will change the relative lengths of the column of mercury and of the solution between the platinum terminals, which means a change in resistance in the bridge arm, and a consequent deflection of the galvanometer. The instrument was stated to be sensitive to a temperature change of 0.00001°, and while it is not adapted to spectrum radiation measurements, it might be used in total radiation work where an elaborate installation is not convenient. By making the receiving bulb of opaque non-conductive material and by covering the inside with lampblack, or platinum black, this would be as complete an absorber ("black-body") as the thermopile or bolometer. Its efficiency would, of course, depend upon the gas inclosed.

II. THE RADIOMICROMETER.

The radiomicrometer is essentially a moving coil galvanometer, of a single loop of wire, with a thermo-junction at one end. This instrument was invented independently by d'Arsonval[2] and by Boys.[3] The former

[1] Weber: Archiv. Sci. Phys. et Mat. (3), **18**, p. 347, 1887.
[2] d'Arsonval: Soc. Franç. de Phys., pp. 30 and 77, 1886.
[3] Boys: Proc. Roy. Soc., **42**, p. 189, 1887.

used a loop, one part of which was silver and the other was of palladium; the latter used a junction of bismuth and antimony, which was soldered to a loop of copper wire.

The sensibility of the Boys instrument was given as $\frac{1}{10\,000\,000}$ to $\frac{1}{54\,000\,000}$ of 1 degree. From subsequent work with other radiation meters in which this high degree of sensitiveness has never been attained, it would appear that the sensibility of the radiomicrometer was overestimated. It certainly has never attained the sensibility of the radiometer, one example of which, used by Nichols (*loc. cit.*, Table V), was twelve times as sensitive as the radiomicrometer of Boys. The latter gave a deflection of a little less than 1 cm. per square millimeter of exposed vane for a candle and scale, each at a distance of 1 meter. Paschen[1] attempted to improve the radiomicrometer, but out of about fifty junctions only three were useful, and these were only three times as sensitive as that of Boys, while the period was about 40 seconds. The long period is not always detrimental, however, for the radiomicrometer is not subject to magnetic disturbances and is a very useful instrument for work not requiring the highest attainable sensitiveness.

The writer has indicated further improvements in the instrument (see Carnegie Publication No. 65) and places it in a vacuum, which increases the sensibility by at least 70 per cent. The instrument was about six times as sensitive as that of Boys for a full period of 25 seconds. Para- and dia-magnetism limited the sensitiveness to this value. The work with this instrument brought out the fact that one is inclined to use too strong field-magnets, and that further progress can be made by using weak magnets, or narrow strong magnet, situated as far as possible above the thermo-junction, so as to avoid the effects of para- or dia-magnetism. The combination of the radiomicrometer and the radiometer is feasible, although the writer found its usefulness as limited as that of the radiomicrometer. When wires can be obtained more free from magnetic material it will possible to construct a more sensitive instrument. It is doubtful, however, whether it will ever surpass the bolometer used with a galvanometer of the highest sensibility. With the radiomicrometer, Lewis[2] was able to investigate infra-red emission spectra of the alkali metals, which are weak in energy. Wilson[3] and Julius[4] have used the radiomicrometer for total and spectral radiation work, and have found the instrument highly satisfactory. The slow period and lack of portability, mentioned by some writers, is certainly not to be weighed against its indifference to magnetic perturbations and constancy of the zero reading. Even a slow period is less objectionable than a quick period instrument

[1] Paschen, Ann. der Phys. (3), **48**, p. 272, 1893.
[2] Lewis: Astrophys. J., **2**, p. 1, 1895.
[3] Wilson: Proc. Roy. Soc., **55**, 1894; **58**, 1895; **60**, p. 337, 1896.
[4] Julius: Handlingen **5**, de Nederlandisch Natuur- en Geneeskundig Congres, 1895.

with which just as much time is lost by repeating observations which may be affected by the lack of constancy of the zero. The instrument is self-contained, and where the greatest sensitiveness is not required, it deserves a wider application.

TABLE IV.—SENSITIVENESS OF RADIOMICROMETERS AND RUBENS THERMOPILE.

Observer.	Full period.	Area of vane.	Deflections in cm/mm² candle and scale at 1 m.
Radiomicrometer:	*sec.*	*mm²*	*cm.*
Boys (Phil. Trans., **180 A**, p. 159, 1889)	10	4	0.9
Paschen (Wied. Ann., **48**, p. 275, 1893)	40	....	3
Lewis (Astrophys. Jour., **2**, p. 1, 1895)	20	1.4	1.3 (?)
Coblentz (Bulletin Bureau of Standards, **2**, p. 479, 1906)............	40	3	3.6
	25	3	6 (in vacuo)
Thermopile:			
Rubens (Wied. Ann., **45**, p. 244, 1898)	14	16 (?)	16 (250 cm. total deflection) 1 mm = $1.1° \times 10^{-6}$ C.

In table IV are given the various radiomicrometers thus far described and their sensitiveness, which is expressed in centimeter deflections per millimeter of exposed vane, for a candle and scale each at a distance of 1 meter.

III. THE THERMOPILE.

From a historical point of view the thermopile has been in use from the very beginning of radiant energy measurements, and in the hands of Tyndall and other pioneers in this domain rendered excellent service in spite of its great heat capacity. For spectro-radiometric work, however, only the linear thermopile of Rubens[1] is well adapted. This thermopile consists of 20 junctions of iron and constantan wires about 0.1 mm. to 0.15 mm. thick (resist 3.5 ohms), and when used with a galvanometer, having a figure of merit of $i = 1.4 \times 10^{-10}$ amp. (period = 14 sec.), a deflection of one scale division indicated a temperature change of $1.1° \times 10^{-6}$. A candle at 5 m. gave a deflection of about 10 cm. or 250 cm. at 1 m. The area of the exposed face is about 0.8×20 mm. The deflections were as rapid as a bolometer, and its stationary temperature was reached in less time than the single swing of the galvanometer needle. In other words, its heat capacity was so small that it gave an accurate register of the energy falling upon it. In another experiment, using a galvanometer sensitiveness of $i = 5 \times 10^{-10}$ ampere, and the scale at 1 m., 1 mm. deflection $= 2.2° \times 10^{-6}$ C. The sensitiveness is the same as that of the best bolometers yet constructed, while its simplicity commends itself even in spectrum radiation work.

The general experience in this country, however, has been that the commercial instrument does not fulfill all the excellent qualities claimed for the one originally described. The wires are heavier than in the original specifications, which makes the instrument sluggish.

[1] Rubens: Zs. für Instrumentenkunde, **18**, p. 65; 1898.

The problem in thermopile construction is to have it of low resistance (equal to that of the galvanometer), of low heat capacity and heat conductivity, and of high thermoelectric power. The latter requirement is fulfilled by using iron and constantan. The heat capacity can be reduced by using finer wire, say 0.06 to 0.1 mm. diameter, and by making the unexposed junctions smaller than the ones to be exposed. The latter are soldered with quite large beads of silver, which are then flattened to present a large surface. The unexposed junctions do not need this, and the small bead formed by the fusion of the two wires (with a bit of silver solder if necessary) can be hammered thin, in order to have it radiate rapidly. By using finer wires the resistance will be increased if the dimensions of the Rubens pile be retained. In the commercial instrument, at least one-third of the wire is between the unexposed junctions and the binding-posts. The greater part of this wire may be eliminated by making the supporting frame narrower, while still retaining the original distance between the exposed and the unexposed junctions. The elimination of this superfluous wire will reduce the resistance by about one-third.

Comparison of Old and New Form of Thermopile.

In order to test these conclusions in regard to the use of finer wire, a new iron-constantan pile of 20 junctions, made of wire 0.08 mm. diameter, was ordered from the makers of the original instrument. Although the specifications were not completely fulfilled (the frame was nearly the same size as the original, which increased the resistance to 9 ohms), the sensitiveness was 1.4 times that of the old type which has resistance of 4.8 ohms (wire about 0.15 mm.). By means of suitable switches the two thermopiles were connected to the same galvanometer, having a full period of 12 seconds ($i=2\times10^{-10}$ amp.) and exposed to the radiation from a Nernst heater. For all deflections, as large as 35 cm., the new thermopile showed no drift greater than 2 mm., which may be attributed to the galvanometer. On the other hand, the zero of the old thermopile would drift 0.5 cm. in a 10 cm. deflection to 2.2 cm. in a 27 cm. deflection and would require 16 to 20 seconds for the deflection to return to its original zero.

The two instruments were then tested in a vacuum. The sensitiveness of the old instrument was increased only 15 per cent, while no change in sensitiveness could be detected in the new one, although two distinct tests were made on different days, the pressure having been reduced to 0.01 mm.

The thermopiles are mounted on ivory frames and are covered with a sheet of copper, one side having a slit, the other a funnel-shaped opening (1 by 15 mm.) in it. The slit was covered and the radiation passed through the funnel. The whole was suspended from a rubber cork in a wide-mouthed bottle, which was exhausted with a mercury or a Geryk pump. The source of energy was an incandescent lamp. With 200 ohms in series with the galvanometer the deflections were about 10 cm. The fact

that the sensitiveness of these thermopiles did not increase appreciably in a vacuum is rather remarkable. Brandes (Phys. Zeit., 6, p. 503) found that a single junction of 0.02 mm. wire became 18 times more sensitive in a vacuum. Lebedew (Ann. der Phys., 9, p. 209) found that a 0.025 mm. iron-constantan junction when black was 7 times, and when bright 25 times more sensitive at a pressure of 0.01 mm. than for atmospheric pressure.

The Peltier Effect.

The result of the Peltier effect is to lower the temperature of the exposed junction. Consequently, the thermopile does not give an accurate record of the energy received. The actual error introduced has never been determined. Since there is a possibility of using the thermopile for quantitative work in place of the bolometer, it is desirable to learn the degree of accuracy of this instrument.

The rate of generation of heat by the Peltier effect is proportional to the current, while the generation of heat on account of resistance is proportional to the square of the current. Jahn[1] has shown that the heat generated by the Peltier effect, determined experimentally, agrees, within experimental error, with the value computed from the observed thermoelectric power. The value for iron-constantan has never been determined experimentally[2] but from the work of Jahn it is permissible to compute the heat generated in the thermopile by using the known thermoelectric power which is about 50×10^{-6} volts.

Using a galvanometer of 5 ohms resistance and having a figure of merit of $i=3\times 10^{-10}$ ampere per millimeter for a scale at 1 m., and an iron-constantan thermopile of 20 junctions, wire 0.08 mm. and 5 ohms resistance, 1 mm.$=2^\circ\times 10^{-6}$ C. The Peltier effect in calories is computed from the formula

$$P=\frac{Tit}{J}\cdot\frac{dE}{dt}$$

where $T=274$; $i=3\times 10^{-11}$ c.g.s.; $t=5$ sec.; $J=4.2\times 10^{-7}$ and $dE/dt=50\times 10^{-2}$ c.g.s. units;

$$P=\pm 5\times 10^{-12} \text{ gr. cal.}$$

The total weight of the junctions is about 0.01 gr. and the specific heat is about 0.1 gram calorie. Hence the temperature change of the exposed junctions is:

$$\Delta t=\frac{5\times 10^{-12}}{0.1\times 0.01}=5^\circ\times 10^{-9} \text{ (for 1 mm. deflection)}$$

[1] Jahn: Wied. Ann., 34, p. 755, 1898.

[2] Since writing this, it has been found that Lecher (Ber. Akad. Wiss. Wien, 115, p. 1505, 1906; Sci. Abstracts, 1083, 1907) has recently determined this constant to be 12.24 gr. cal. per amp. hr., while the value previously computed was 10.5 gr. cal. per amp. hr.

and since the temperature of the unexposed junctions is changed an equal amount in the opposite direction the total $\Delta t = 1^\circ \times 10^{-8}$. But a deflection of 1 mm. $= 2^\circ \times 10^{-6}$ C., hence the error is 1 part in 200 under the best theoretical conditions. In practice the temperature sensitiveness will not be so great; it will be shown presently to be of the order $5^\circ \times 10^{-6}$, whence the Peltier effect would cause an error of 1 part in 500, or 1 mm. in 50 cm., which is as close as one can read such large deflections.

Since the Joule heat depends upon the square of the current it is negligible. Further consideration of the thermopile as an instrument for quantitative measurements will be found below in connection with the bolometer.

It will be noticed presently that prior to his construction of the iron-constantan thermopile, Rubens had used several very sensitive bolometers, all of which were displaced by the thermopile. For exploring spectra with very narrow lines, the linear bolometer is probably better adapted than the pile which, however, may be covered with a diaphragm, having a narrow slit. For extreme sensitiveness it equals the bolometer, and it is a noteworthy fact that all the investigations in the extreme infra-red and ultra-violet parts of the spectrum, where the energy is weak, have been accomplished by means of the thermopile. Unless one can build up an elaborate permanent bolometric apparatus in a room not exposed to direct sunlight, the thermopile will give the more reliable readings, as far as the constancy of the zero is concerned. Whether or not the thermopile will give a true reading of the energy falling upon it will depend upon the manner in which it is employed. It requires no particular skill to manipulate, and is easier to protect against temperature changes than is a bolometer with its storage battery. The "drift" in bolometers to be noticed presently was found in the old thermopile when used with a very delicate galvanometer. This was not due to unequal increments of resistance as in the bolometer, but to thermoelectric effects at the binding screws, to the connecting wires moving in the earth's magnetic field, and principally to the large heat capacity of the junctions. Most of these disturbances, however, are small and easily avoided in the Rubens type of thermopile. Since the bolometer strips and the balancing coils are of dissimilar material, it is also as subject to thermoelectric disturbances.

IV. THE RADIOMETER.

The manner in which an interesting scientific toy can be made to serve a useful purpose is well exemplified in the radiometer of Crookes,[1] discovered about 1875. By fastening bits of pith (the one black, the other white) at the ends of a long straw, which was suspended by means of a silk fiber in a long glass tube, he was able to make measurements of

---

[1] Crookes: Phil. Trans. (II), 166, p. 325 1876.

radiant energy, even at that early date. Pringsheim[1] simplified the instrument somewhat, suspended the vanes bifilarly with silk thread, and used it to investigate the infra-red spectrum of the sun to about 1.5 μ, produced by means of a glass prism. From this, the first really useful radiometer was developed by Nichols.[2] The behavior of the radiometer has been worked out theoretically by Maxwell[3] in his paper on "Stresses in Rarefied Gases arising from Inequalities of Temperature." Among other things he showed that for two parallel disks very near each other the central points will produce but little effect, because between the disks the temperature varies uniformly, and only near the edges will there be any stress arising from an inequality of temperature in the gas. It has been shown by others, especially by Crookes and by Nichols, that the sensitiveness of the radiometer is a function of the pressure of the residual gas, of the kind of gas surrounding the vanes, and of the distance of the exposed vanes from the window. The latter, on account of its absorption, of course limits the region of the spectrum which is to be investigated. If the vanes are not too close to the window, the deflections will be proportional to the energy falling upon one of them.

Comparison of Sensitiveness and Area of Vane.

For veins of finite dimensions, such as must be used in practical work, the writer has found that the deflections are proportional to the area of the exposed surface of the vane. This is perhaps to be expected, although there seemed to be some doubt. The curve of deflections and exposed area of vanes (area 10.5×1.3 mm. for constant pressure of 0.02 mm.) does not pass through the origin. One explanation may be that for infinitely narrow vanes the graph is not a straight line, but curves as it approaches the origin. Because of the impracticability of suspending vanes of different widths successively from the same fiber suspension, at the same distance from the window, using the same gas pressure for all vanes, it was necessary to use one wide vane, with a slit before it, and vary the opening of the slit. The source of energy (Nernst heater) was at a distance of 3 meters and, hence, the width of the projection of the slit upon the vane was practically the width of the slit, except for a very narrow slit when diffraction may decrease the energy incident upon the vane. This, however, would displace the graph still farther from the origin. The forces acting in a radiometer are so complex and so little understood that no further examination was made to ascertain the limits within which the above proportionality holds. The test was made to reduce the deflections to unit area between the above limits of exposed vane. It is of interest to note in this connection that in a bolometer the sensitiveness varies as the square root of the area of the bolometer strip.

---

[1] Pringsheim, Ann. der Phys. (3), **18**, p. 32, 1883.

[2] Nichols: Phys. Rev., **4**, p. 297, 1897; Berl. Ber., p. 1183, 1896.

[3] Maxwell: Collected Papers, **2**, p. 681; Phil. Trans., Part I, 1879.

In his earlier communications the writer held to the belief that the weight of the vanes and their size were the most important factors in determining the sensitiveness and period of a radiometer. However, so many factors enter into the problem that it is difficult to decide this point, and the following test may be of interest, showing that the sensitiveness is determined principally by the diameter of the quartz fiber suspension.

Comparison of Sensitiveness and Diameter of Fiber Suspension.

Using the same vanes (0.5×9 mm. area) the sensitiveness and period were found for a heavy and a light quartz fiber suspension. The main difficulty was to insure that the vanes were at the same distance from the window, and that the pressure was the same in the two cases. Hence these qualities are only approximate. In table V, it will be noticed that in changing from a heavy to a light fiber the sensitiveness is increased 4.5 times while the period was increased almost threefold. It further shows that for the same (light) fiber the sensitiveness was doubled (36 to 71 cm. per mm.) by changing the pressure and the distance from the window, which was of fluorite, and hence opaque beyond 10 μ. The sensitiveness of 71 cm. per square millimeter of exposed area is the highest on record. This, however, was not the maximum sensitiveness since the pressure was 0.02 mm., while radiometers have their maximum sensitiveness at a pressure of about 0.05 to 0.1 mm. At this pressure, however, heat conduction would cause annoyance.

The vanes of this suspension were of platinum foil 0.01 mm. thick, covered on one side electrolytically with platinum black, and then smoked over a candle. (It is best to cool the gases from the flame by placing a wire gauze or sheet of metal full of holes between the flame and the vanes when smoking them.) These vanes were suspended by means of one of the finest workable quartz fibers, and when within 3 mm. of the window either one of the vanes would always approach and adhere to it, even at atmospheric pressure. From tests with fluorite windows, which from internal strains might be piezoelectric, and with rock-salt windows, when bare, and also when covered with tinfoil, it was found that this effect is not due to electrification. Starting with the vanes parallel, and at a distance of about 5 mm. from the window, it was found that as this distance was decreased one of the vanes (generally the one to be exposed to radiation) would approach the window, and for a distance of about 3 mm. would turn until the plane of the vanes was at right angles to the window. The observations extended over several months, and all evidence indicates that this effect is due to gravitational attraction. As a result of this the deflection of such a vane would not be proportional to the energy received. The radiometer had no torsion-head to control the zero. However, for general work with very sensitive radiometers a torsion-head would be necessary, since the best pumps may leak, which will cause a slow "drift."

It will be shown presently that this is about five times the sensitiveness of Snow's bolometer, for which 1 mm. deflection (scale at 3 m.) indicated a temperature difference of $7.5° \times 10^{-6}$. In other words, this radiometer would detect $\frac{1}{1\,000\,000}$ degree rise in temperature. But the period of the radiometer was 6 times that of the bolometer, which is its weakest point in radiation work requiring a short period.

TABLE V.—SENSITIVENESS OF RADIOMETERS.

Pressure.	Full period.	Deflection per square mm.	Remarks.
mm.	*secs.*	*cm.*	
0.02	45	7.9	Vanes (area 0.5×9 mm., weight 5 mg.) 3 mm. from window.
.02	60	11.5	Vanes closer to window.
SAME VANES (0.5×9 mm.), FINER QUARTZ FIBER.			
mm.	*min.*	*cm.*	
0.02	2	36	Vanes 3 mm. from window candle at 3 m.
.03	2.5	71	Vanes nearer window. This is the greatest recorded sensitiveness. A deflection of 1 mm. on scale at 1 m. $= 3.8° \times 10^{-6}$.
.04	....	63.5	
HEAVY VANES, AREA 1.3×10.5 mm., WEIGHT 10+mg.			
mm.	*secs.*	*cm.*	
0.02	40	5.5	Distance of vanes from window unknown.
.02	60 to 64	13.7	Vanes nearer window, hence longer period.
.026	36 to 40	8.5	Vanes farther from window than in preceding.
.035	25	3.3	Vanes still farther from window, which shortens period and decreases sensitiveness. For a pressure of about 0.05 mm. the sensitiveness would be much greater.

A comparison can also be made (table V) between light vanes (0.5×9 mm.) and heavy ones (1.3×10.5 mm.) at the same pressure but having different quartz-fiber suspensions. The results show that while the light weight vanes are more sensitive than the heavy ones (see table V), there seems to be no limit to the sensitiveness attainable in either case, provided one does not consider the period. The idea of not considering the period of vibration with sensitiveness seems reasonable, for by sensitiveness is meant the minutest quantity of radiation one can detect, assuming one is willing to wait for the deflection to reach a maximum. In table VI are compiled the most notable radiometers used in radiation work. The use of a candle as a standard of comparison is questionable, but since the sensitiveness of the various instruments varies by a factor from 2 to 20, it is sufficiently accurate for the present comparison. In this table it will be noticed that for the same period the various radiometers vary in sensi-

tiveness by as much as 50 per cent. Porter's radiometer was the most sensitive of the instruments having a period of 90 seconds. But he gained little, on the whole, for the vanes were so light that he could work only during the quiet hours at night. On the other hand, the writer,[1] after trying light vanes, adopted the heavy ones, and was thus able to work at all hours, even with a large air-compressor in operation, in an adjoining room.

TABLE VI.—SENSITIVENESS OF VARIOUS RADIOMETERS.

Observer.	Full period.	Area of vanes.	Deflections per square mm. area of exposed vane; candle and scale each at 1 m.
	min. sec.	*sq. mm.*	*cm.*
E. F. Nichols:	0 12	2×15	5 (?)
Phys. Rev., **4**, p. 297, 1897			
Astrophys. Jour., **13**, p. 101, 1901	0 11	3.1	12.5
Stewart:	1 20	30	4.9
Phys. Rev., **13**., p. 257, 1901	5		17
Drew: (Phys. Rev., **17**, p. 321, 1903)	1 30	7	17.1
Porter (Astrophys. Jour., **22**, p. 229, 1905)	1 30	3.6	27.5
Coblentz	1 30	15 (10×1.5)	8 to 10
Abs. Spectra	50	12	10 to 12
Phys. Rev., **16**, **20**, and **22**. (Vac. tube)	1 40	11 (11×1)	52
Another vane	2 30	4.5	71
(*Ibid.*)	1 10	4.5	35

SENSITIVENESS COMPARED WITH WAVE-LENGTH OF EXCITING SOURCE.

In his investigations of emission spectra of the alkali metals, using a bolometer, and a prism and lenses of quartz, Snow[2] found that the vapor of the carbon arc had the larger portion of its energy concentrated in one large band in the violet. The writer,[3] using a radiometer, a rock-salt prism, and a mirror spectrometer for investigating infra-red emission spectra, found that the radiometer gave but small if any deflections in the violet. The violet band is far enough from the reflection minimum of silver not to be weakened by it, hence it appeared that the radiometer might be selective in its behavior to radiant energy.

To test this point the following experiment was tried. The total radiation from an aluminum spark (with glass plate condenser) on a 10,000 volt transformer was measured with a very sensitive radiometer (period 65 to 70 seconds; sensitiveness 35 cm. per square millimeter) just described, and with a bolometer, to be described subsequently. The window of the radiometer was of white fluorite 2 mm. thick, hence transparent to the ultra-violet, but opaque beyond 10 μ. A large point of the energy of the aluminum spark lies in the ultra-violet. The maximum energy of the warm electrodes occurs at about 8 μ. The radiation from the spark

[1] "Investigations of Infra-red Spectra," Carnegie Publication No. 35, 1905.
[2] Snow: Phys. Rev., 1, pp. 28 and 221, 1893.
[3] Carnegie Publication No. 35, Part II, 1905.

passed through a quartz cell 8 mm. thick, containing distilled water which absorbed all of the infra-red energy. The observations consisted in obtaining the ratio of energy transmitted by a glass plate 8 mm. thick (which is opaque to rays shorter than 0.3 μ) to the total energy of the spark.

Unfortunately, at the high sensitiveness required for ultra-violet radiation the two instruments were not in perfect working order at the same time. During the first test the bolometer had a short period, 10 seconds, and caused trouble by the "drifting" of the zero with changes in the spark, while in the second test the radiometer was leaking slightly, which caused its zero to "drift." Then, too, the spark was by no means constant, but, as will be seen presently, the ratio above referred to is about the same for the radiometer and the bolometer, after correcting for the loss of 4 per cent by reflection at the fluorite window. The agreement is close enough to show that the radiometer is not selective in its action and hence is adapted to investigations in the ultra-violet.

In the first test the direct radiation from the aluminum spark (with condenser) was compared with the part transmitted by glass. There was some infra-red energy in this case which made the ratio lower than in the second experiment. The direct deflections with the radiometer were about 20 cm. The ratio of the deflection through a piece of plate glass to the direct deflection varied from 17 to 19.5 per cent (mean about 18 per cent), while with the bolometer the same ratio varied from 16 to 20 per cent, the mean being about 19 per cent. The bolometer followed the flunctuations of the spark, hence the greater variations. The spark was 75 cm. from the radiometer and 25 cm. from the bolometer.

In the second test the infra-red radiation was absorbed by a cell of water, with quartz windows. Plate glass was again used to absorb the ultra-violet. In this test, the ratio of the radiation transmitted by the glass to the total radiation was on an average about 65 per cent, while the same ratio for the bolometer was 67 per cent. Correcting for the loss by reflection at the window the ratio for the radiometer would be about 69 to 70 per cent.

The results show that the radiometer is not selective, *i.e.*, it is as efficient in the ultra-violet as in the bolometer.

THE RADIOMETER COMPARED WITH THE BOLOMETER.

In discussing the merits of the radiometer, writers have generally emphasized the fact that the radiometer is not adapted for quantitative work since it cannot be calibrated. As a matter of fact, in reviewing the work done in radiation it was found that even with the bolometer there are only a few cases where the energy was obtained in absolute measure. Even in the study of the laws of radiation from a hollow enclosure or Kirchhoff radiator (so-called "black-body"), the direct galvanometer deflections were observed and reduced to a single standard of sensitive-

ness which was in arbitrary units. The same may be done with the radiometer. Its sensitiveness is easier to control, since it can be made to depend only upon the pressure of the residual gas — the constant of a galvanometer varies continually. It is not affected by magnetic effects, and a heavy vane is less affected by earth tremors than is a very light galvanometer suspension. It is sensitive to temperature changes, but less so than the bolometer, and it can be more easily shielded from temperature changes than can a bolometer with its galvanometer, battery, etc. The fact that it is not portable is not a serious drawback, since it is not usually necessary to move the instrument. It has two disadvantages, viz, its window, or preferably double window, is selective in its transmission, and its period is somewhat longer than that of a bolometer and galvanometer of equal sensitiveness. But the latter is nearly always drifting and to repeat one's readings it takes as long for an observation as it does with a radiometer.

Since the weight is of minor importance, tremors are avoided by having the suspension weigh about 8 to 10 mgs. When used with a good mercury-pump, it requires no attention after it is properly adjusted. A delicate galvanometer requires frequent adjustment and in connection with a bolometer the investigator's time is occupied principally with the care of the instrument (at least that has been the writer's experience), which should be a secondary matter. The two instruments are of the same order of sensitiveness, with the possibility of the radiometer being the more sensitive.

This is well illustrated in the test for their efficiency to ultra-violet radiation, where both instruments were at about their maximum working sensitiveness. The bolometer used was 0.22 by 10 mm. in area, resistance 2.8 ohms, and for a battery current of 0.04 amp. with a galvanometer sensitiveness of $i=1.5\times10^{-10}$ amp. (period 16 seconds) had a temperature sensitiveness of 9×10^{-6} per millimeter deflection, on a scale at 1 m. (see table VII). (A Nernst heater was also used in making the comparison.)

A candle at 1 m. gave a deflection of 45 cm. which, on the assumption that the sensitiveness is proportional to the square root of the area of bolometer strip, is 30 cm. per square millimeter. For the radiometer having a vane 0.5 by 9 mm. a candle gave a deflection equivalent to 159 cm. at 1 m. or, since the deflection is proportional to the area of the exposed vane, 35 cm. per square millimeter (table VI). In other words, the radiometer was 1.2 times as sensitive as the bolometer, or 1 mm. deflection corresponded to $7.5^\circ\times10^{-6}$ C. (For a full period of 2.5 minutes its sensitiveness was $3.8^\circ\times10^{-6}$ C.) Its period, however, was 4.5 times that of the bolometer. This estimation of sensitiveness is based on the assumption that the radiometer was as complete an absorber of energy as the bolometer. Judging from its period, its efficiency is much lower than

that of a bolometer, hence the radiometer must be sensitive to temperature changes less than the value just given.

The sensitiveness of bolometers thus far attained is about $\frac{1}{1\,000\,000}$ degree per millimeter deflection. Paschen claims a sensitiveness of $\frac{1}{10\,000\,000}$ degree by reading to 0.1 mm. But the conditions are rare when one can read to 0.1 mm., so that the estimate would seem too high. As will be seen presently, the working sensitiveness is of the order of $\frac{5}{1\,000\,000}$ degree, or generally considerably less.

V. THE BOLOMETER WITH ITS AUXILIARY GALVANOMETER.

We have now to consider one of the most useful radiation meters yet devised, viz, the bolometer which is simply a Wheatstone bridge, two arms of which are made of very thin blackened metal strips of high electrical resistance and high temperature coefficient, one or both of which are exposed to radiation. When thus exposed, their temperature changes, thus unbalancing the bridge, and the resulting deflection of the galvanometer gives a measure of the energy absorbed. The maximum sensitiveness of the bolometer is limited by the size of the strip and is proportional to the square root of the surface exposed to radiation. Any further gain in sensitiveness must be attained by increasing the sensitiveness of the galvanometer, which, for the moving magnet type, varies as the square of its (undamped) period. The sensitiveness is also proportional to the bolometer current, which is limited by the resistance of the bolometer strips.

It will be noticed presently that the working sensitiveness of the various galvanometers thus far used is of the order of 2×10^{-10} amp. per millimeter deflection, while the temperature sensitiveness varies from $5^\circ\times10^{-5}$ to $5^\circ\times10^{-6}$ for 1 millimeter deflection for a scale at 1 meter.

Historical.

The various bolometer-galvanometer apparatus will first be noticed, in so far as it relates to spectro-radiometric work.

The first great step in improving the moving magnet galvanometer is due to Kelvin who decreased the weight of the moving parts to a few milligrams, and introduced the astatic system of magnets. The main problem in bolometer construction is to use strips of a metal having a high resistance-temperature coefficient, a small specific heat, and low heat conductivity. These metals are nickel, platinum, tin, and iron, but for various reasons in mechanical construction, platinum is the most commonly used.

The manner in which this instrument has been developed to its present high sensitiveness is best illustrated by considering the various designs of different investigators, given in table VII.

TABLE VII.—BOLOMETER-GALVANOMETER SENSITIVENESS.

Observer.	Galvanometer.			Bolometer.		
	Resistance.	Full period.	Current sensitiveness for 1 mm. deflection.	Resistance.	Area.	Bolometer current.
	ohms.	*sec.*		*ohms.*	*sq. mm.*	*amp.*
Langley (Annals Astrophys. Obs.)	......	......	1 to 5×10^{-10}	4	0.05 to 0.02 $\times 12$	0.03
Abbot (Astrophys. J., **18**, p. 1; 1903)	1.6	20	5×10^{-11}	.....	....	....
Ångström: Wied. Ann., **26**, p. 253; 1885	......	......	....	.....	....	....
Wied. Ann. **36**, p. 715; 1889	......	......	....	.....	0.1×12	....
Wied. Ann., **48**, p. 497; 1893	8	16	5.7×10^{-9}	5	....	....
Julius (Licht und Wärmestrahlung, p. 31; 1890)	2.7	......	4×10^{-9}	3	0.3×14	0.133
Helmholtz (Verh. Phys. Gesellsch., Berlin, **7**, p. 71; 1888)	......	......	8×10^{-9}	8.8	....	....
Lummer and Kurlbaum: Zs. für Instrumentenkunde, **12**, p. 81; 1892; Wied. Ann., **46**, p. 204; 1892	......	......	1.5×10^{-9}	60	$12 \times 1 \times 32$	0.006
Rubens: Wied. Ann., **37**, p. 255; 1889	5	4 to 5	3.2×10^{-10}	5.2	$7 \times 0.3 \times 35$	0.2
Wied. Ann., **45**, p. 238; 1892	80	......	3.2×10^{-10}	3	$3 \times 0.2 \times 10$	....

TABLE VII. — BOLOMETER-GALVANOMETER SENSITIVENESS.

Temperature sensitiveness.			Candle test.				Remarks.
For 1 mm. deflection and period given in col. 3.	Ibid., for a scale at 1 m.	Ibid., for a scale at 1 m. and a full period of 15 secs.	Distance of candle.	Distance of galvanometer.	Observed deflection.	Equivalent deflection per mm² area for candle and scale at 1 m.	
°C.	°C.	°C.	met.	met.	cm.		
1×10^{-6}	...	...	...	...	...	...	In practice for solar spectrum work a full period of 3 secs. and $i = 2.2 \times 10^{-9}$ ampere is used. Balancing coils of platinoid. Bolometer is inclosed in water jacket.
...	...	...	...	...	...	...	In practice drifting is minimized by placing a short copper wire in series with one of the bolometer arms.
...	...	...	...	...	...	...	Surface bolometer; 23 strips of tin foil; blackened with $PtCl_2$ and soot. Balancing coils of copper wire in separate box. Sensitiveness 556×10^{-9} gr-cals/cm²/sec.
...	...	...	...	2	...	...	Single Pt. strip 0.1×12 mm. in spectrobolometer.
9×10^{-5}	...	...	...	...	...	...	2 arms of tin foil in form of grating. Sensitiveness also given as 127×10^{-9} gr- cals/cm² sec.
...	...	...	...	...	...	...	Bolometer strips of nickel 0.002 mm. thick. Balancing coils of platinum wire in oil in separate box. Found deflection proportional to current.
8×10^{-5}	...	...	...	...	...	...	Surface bolometer, 4 similar arms, so no compensating resistances needed; diagonally opposite arms exposed. Sensitiveness also given as 533×10^{-9} gr-cals/cm²/sec.
3×10^{-4}	...	...	1	...	800	...	Surface bolometer 4 similar arms of platinum foil 0.001 mm. thick; 2 diagonally opposite arms exposed to radiation surface consists of 12 strips of platinum, 1 mm. wide×32 mm. long, separated by 1.5 mm., back of which openings are 12 similar strips of the diagonally opposite arm. Bolometer currents as high as 0.04 ampere could be used.
2×10^{-4}	...	...	...	...	...	...	Surface bolometer of tin foil 0.01 mm. thick; 7 strips in each arm.
5×10^{-6}	2.5×10^{-5}	4×10^{-5}	1	5	60	5	2 arms of 0.04 mm. iron wire hammered flat; 3 strips in each arm.

TABLE VII — CONTINUED.

Observer.	Galvanometer. Resistance.	Galvanometer. Full period.	Galvanometer. Current sensitiveness for 1 mm. deflection.	Bolometer. Resistance.	Bolometer. Area.	Bolometer. Bolometer current.
	ohms.	*sec.*		*ohms.*	*sq. mm.*	*amp.*
Rubens: Wied. Ann., **45**, p. 238; 1892	80	....	3.2×10^{-10}	80	0.09×12	....
Rubens and Snow (Wied. Ann., **46**, p. 529; 1892)	150	20	1.8×10^{-11}	80	0.09×12	....
Snow (Phys. Rev., 1, p. 31; 1893)	140	20	1.5×10^{-11}	75	0.05×7	0.025
Aschkinass (Wied. Ann., **55**, p. 401; 1895) ..	......	20	6×10^{-11}	13	....	0.04
Donath (Wied. Ann., **58**, p. 609; 1896)	......	......	6×10^{-12}	5	....	....
Paschen (Wied. Ann., **48**, p. 272; 1893)	*60	7	2.3×10^{-11}	.....	....	0.01 to 0.02
	*60	15	3.3×10^{-12}	.....	....	....
	20	30	1.6×10^{-11}	12	$3\times0.5\times15$	0.03
	..	34	8.3×10^{-12}	8	0.25×7	.02
Coblentz	5.2	10	2.5×10^{-10}	.....	....	....
	5.2	16	1.5×10^{-10}	2.8	0.22×10	0.02
Rubens Thermopile	5	14	1.4×10^{-10}	3.5	0.8×20	....
Coblentz Radiometer	......	70 ..	....	.....	0.5×9	....
	......	150 ..	....	.....	0.5×9	....

*Galvanometer; 4 coils 40 mm. external and 5 mm. internal diameter, 1,200 turns of graded wire in each coil; moving system, 13 magnets in each group, 1 to 1.5 mm. long, on both sides of glass staff, and 0.3 mm. apart; mirror 2 mm. diameter × 0.03 mm. thick. Total weight of system = 5 mg.

TABLE VII — CONTINUED.

Temperature sensitiveness.			Candle test.				Remarks.
For 1 mm. deflection and period given in col. 3.	Ibid., for a scale at 1 m.	Ibid., for a scale at 1 m. and a full period of 15 secs.	Distance of candle.	Distance of galvanometer.	Observed deflection.	Equivalent deflection per mm^2 area for candle and scale at 1 m.	
°C.	°C.	°C.	met.	met.	cm.		
8×10^{-6}	4×10^{-5}	....	1	5	12	2.7	2 arms of 0.005 mm. platinum wire hammered flat. Deflections of galvanometer proportional to current through bolometer and rise in temperture of arms proportional to incident energy.
3×10^{-6}	....	....	....	....	40	......	For Hefner candle at 1 m.
8×10^{-6}	2.4×10^{-5}	4×10^{-5}	1	3	15	8.3	2 bolometer arms of platinum 0.000936 mm. thick; balancing coils of German silver; 4-coil galvanometer, total of 7200 turns, wound with two sizes of wire. Magnet system of 12 magnets 3 to 4 mm. long; total weight of system 80 mg.
3×10^{-5}	1.2×10^{-4}	....	....	4	....	......	2 bolometer arms of 3 iron wires hammered flat.
....	....	....	....	....	....	......	2 arms of platinum 0.17 mm. wide × 0.0074 mm. thick; balancing coils (of platinum) of elaborate design in separate box. Drifting was serious.
....	....	....	....	....	....	......	Bolometer arms of platinum 0.001 to 0.0005 mm. thick. Compensation resistances of manganin wire, final adjustment on platinum wire with mercury contact.
....	....	....	....	3	....	......	
1×10^{-6}	2.7×10^{-6}	11×10^{-6}	....	2.7	....	......	
84×10^{-7}	2.1×10^{-5}	8×10^{-5}	....	2.5	....	......	
....	....	....	....	....	....	......	Using an 8-magnet system and a full period of 20 secs. $i = 8 \times 10^{-11}$ ampere, while a 6-magnet system had a sensibility of $i = 2.5 \times 10^{-11}$ ampere for a full period of 36 seconds.
....	9×10^{-6}	9×10^{-6}	1	1	45	30	
1.1×10^{-6}	....	1×10^{-6}	5	(1?)	10	15	
....	†7.5×10^{-6}	....	2.3	1	30	35	
....	†3.8×10^{-6}	....	3	1	35.5	71	

†These values are obtained by comparing the deflections per unit area with the bolometer.

Comparison of Sensitiveness of Various Bolometer-Galvanometer Combinations.

The most important data on sensitive radiation meters, and particularly that relating to bolometers, is given in table VII. It will be noticed that the thermopile is as sensitive as the bolometer. The sensitiveness of the radiometer is obtained by comparing it with the bolometer. Although the radiometer is no doubt less efficient than the bolometer, it probably absorbs as much of the incident energy. Since the radiometer deflections were larger, per unit area, than the bolometer deflections, it is safe to assume that the radiometer was just as sensitive as, if not more so than, the bolometer. The long period is of course a serious objection in certain classes of work. In table VII it will be noticed that the high temperature sensitiveness of the various instruments has been attained by the use of a highly sensitive, long period, galvanometer, by using a large bolometer current and by placing the scale at a great distance from the galvanometer. Assuming that the sensitiveness is proportional to the square of the period (undamped) for a scale at 1 m. and a bolometer current of 0.04 ampere, it will be noticed from column 10, table VII, that the temperature sensitiveness of the various instruments falls in two groups. To the first group belong the earlier instruments of Rubens, of Snow, and of Paschen, with a sensitiveness of about $5^\circ \times 10^{-5}$ per millimeter deflection. To the second group belongs a more sensitive combination of Paschen's, and the writer's instrument, in which 1 mm. deflection corresponds to a rise in temperature of $11^\circ \times 10^{-6}$ and $9^\circ \times 10^{-6}$ C., respectively. In other words, the instruments of the latter group have the same sensitiveness, and any increase in the same is to be attained by increasing the scale distance; the bolometer current of 0.04 amp. is about the limit for accuracy. The sensitiveness of the writer's instruments could have been further increased by lengthening the scale distance to 2.5 m., when the temperature sensitiveness would have been $3.6^\circ \times 10^{-6}$, and by doubling the galvanometer period, when the sensitiveness would have been $9^\circ \times 10^{-7}$ against Paschen's $1^\circ \times 10^{-6}$. Such a computation is, of course, illusory on account of damping in the galvanometer. On actual trial (but not for the magnet system quoted) for a full period of 30 seconds the sensitiveness of the galvanometer was $i = 7 \times 10^{-11}$ ampere.

Comparison of a Bolometer with a Thermopile.

The efficiency of the bolometer and the thermopile is reduced by losses due to reflection and radiation from the receiving surface, and by heat conduction to the unexposed parts. The loss of energy in the thermopile due to the Peltier effect has been considered in discussing that instrument. The loss of energy due to reflection is about 4 per cent (Kurlbaum, *loc. cit.*). Assuming the bolometer to be made of platinum 0.5×0.002 mm. cross-section, and the thermopile of 20 junctions of iron and constantan

wire 0.06 mm. diameter, it can be readily shown that the cross-section of the thermopile is about 56 times that of the bolometer, and from their heat conductivities, for the same temperature gradient, that the loss of heat by conduction in the thermopile is about 100 times that of the bolometer. But the temperature gradient at the ends of a bolometer strip carrying an electric current may be 50° to 100° C., so that the heat lost by conduction may be about the same for both instruments. Since the temperature of the bolometer is from 50° to 100° C. higher than the thermopile, the loss of heat per second due to radiation in the former is from 2 to 3 times that of the latter. But the mass of the thermopile is 5 times, while its specific heat is 3.3 times, that of the bolometer. Hence, to raise the temperature of thermopile and the bolometer to the same extent, 16 (5×3.3) times as many heat units must be supplied to the former. Since the loss by radiation is 3 times as great from the bolometer, it will require about 5 times as long for the thermopile to reach a steady temperature. In practice, however, on account of the blackening of the surface, the bolometer is not so quick in its action as here computed.

From these considerations, as well as the mechanical difficulties in constructing a thermopile of wire less than 0.05 mm. in diameter (and keeping the resistance low), it will be seen that the thermopile can not be made so quick in its action as the bolometer and hence is not so well adapted where a quick automatic registration of the galvanometer deflections is desired. But, as will be shown presently, since it is difficult to read large deflections accurately in less than a 4 to 5 second single swing of the galvanometer system, a thermopile of 0.06 to 0.08 mm. wire, which attains a steady temperature in this interval of time, is not objectionable, and, since it is less disturbed by air-currents (being at room temperature), it may be the more reliable instrument (see table IV). Neither instrument, however, compares with the radiometer in steadiness. The amount of work done on emission, absorption and reflection spectra, as well as the accuracy attained, in the infra-red to 15 μ, where the radiometer deflections were, again and again, only a few tenths of a millimeter would not have been possible with these instruments. In a recent examination of reflection spectra of minerals, using a thermopile, the accuracy attainable without repeating the readings several times was far from that of the radiometer, although the actual deflections were larger.

The present experimental comparison of the thermopile, of 0.08 mm. iron and constantan wire, and the platinum bolometer was undertaken in order to determine the accuracy attainable in measuring a constant source of radiant energy, and hence to learn the feasibility of substituting the thermopile for the troublesome bolometer. Within experimental error it has been established by Langley, by Rubens and by Julius that the bolometer (galvanometer) deflections are proportional to the current flowing through the bolometer, and also to the amount of energy falling upon the

bolometer strip. It remains, therefore, to determine whether the present bolometer behaves likewise, and also whether the same accuracy is attainable with the thermopile.

To this end a bolometer was constructed with the greatest care. It was annealed before adjusting the resistance of the strips, covered electrolytically with platinum black (after the method of Kurlbaum) and then smoked over wire gauze over a paraffin candle. The resistances of the bolometer strips were 1.782 and 1.797 ($\Delta=0.015$) ohms, respectively. After blackening them they were 1.766 and 1.818 ($\Delta=0.052$) ohms, respectively. The width of the bright strips was 0.5 mm., which increased to 0.56 mm. after blacking. The length was 11 mm. and thickness less than 0.002 mm. The bolometer current was 0.04 ampere and throughout the following experiments there was no difficulty due to air-currents, or drift. Magnetic disturbances were at a minimum, and, as a whole, conditions for accurate measurements were as perfect as one would expect.

The thermopile of 0.08 mm. wire (20 junctions covered with a slit 0.5 mm. wide) already described, showed a slight lag in registering the energy received. Although this was not marked, there was a tendency for the deflection to creep, instead of stopping abruptly as in the case of the bolometer. This was most marked in large deflections, and necessitated exposing the thermopile to radiation for a definite time (6 seconds) and taking the zero at the expiration of an equal interval of time. The results are given in table VIII. The last two values for the thermopile are vitiated by radiation from the rotating disk, to be noticed presently. The results show that there is no great difference in the two instruments. It was necessary, however, to note the time of exposure of the thermopile, which is not convenient for large deflections. The estimation of the relative merits of the bolometer and the thermopile is, therefore, a personal one, and from the experience gained it may be said that for measuring intense sources the bolometer is the more accurate (when working to 0.5 per cent) unless great precautions be taken in making the thermopile readings.

The theoretical temperature sensitiveness of the thermopile was considerably greater than that of the bolometer, as was found on subsequent computation. It may be added, therefore, that if the bolometer sensitiveness had been increased, by increasing the current through it, there would have been greater unsteadiness in the galvanometer readings.

Experiment with a Sectored Disk.

In comparing the relative merits of the bolometer and the thermopile, the simplest method appeared to be to reduce the intensity of the source by a known amount, by using a sectored disk, the angular openings of which are accurately known. It will be noticed that while the ratios of energy transmitted by the sectored disk were in close agreement in any series of measurements (see tables VIII and IX) the numerical values were

in all cases higher than the true ones. In other words, the disk transmitted too much energy, or the apparent opening was larger than the true one. It remained, therefore, to be shown whether this was due to diffraction (of the very long wave-lengths) or to lack of proportionality in the registering of the energy by the bolometer and the thermopile. The method of observation consisted in taking from 5 to 10 readings without the disk, then a similar number with the rotating disk interposed, followed by a number without the disk.

TABLE VIII.—COMPARISON OF BOLOMETER AND THERMOPILE.

Direct deflection (mean value).	Deflection with disk, 180°−49.9 (mean value).	Ratio.	Direct deflection (mean value).	Deflection with disk, 180°−49.9 (mean value).	Ratio.
Bolometer:			Thermopile:		
May 24, '07:			May 24, '07:		
12.22	6.14	*50.24	13.14	6.61	†50.26
12.16	6.11	*50.24	14.22	7.21	‡50.7
			14.30	7.24	‡50.6

* Nernst heater on 98 volts at 1 m. from bolometer. Galvanometer (full) period 8 seconds undamped; 50 ohms in series. Total deflection about 80 cm. Bolometer is perfectly steady and comes to rest abruptly. Readings vary from 0.1 to 0.7 per cent from mean of about 10 in each set. Temperature sensitiveness $= 6° \times 10^{-6}$.

† Conditions same as for bolometer. Thermopile deflection "creeps," and does not come to rest in same time as galvanometer (on open circuit or with bolometer), due to its larger heat capacity. Galvanometer single swing of 4 seconds increased to 6 seconds and is fully damped, due to lag of thermopile; 50 ohms in series with galvanometer. Temperature sensitiveness $= 2° \times 10^{-6}$.

‡ Source and disk nearer screen. Difficult to read deflection on account of "creeping," which amounts to 1 to 3 mm. Readings made at end of 6 seconds vary by 0.4 per cent from mean; 20 ohms in series with the galvanometer. Temperature sensitiveness $= 5° \times 10^{-6}$.

The first test made was to determine whether the rotating disk (30 cm. diameter, 1.3 m. from the bolometer) affected the instrument; and it was found that the resulting deflections 1 to 2 mm. were no larger than those due to stray radiation reflected from the stationary disk. A heavy black cardboard shield was then placed between the bolometer and the disk (0.5 m. from the disk) and similar screens were placed around the source, which was 2 m. from the bolometer. No radiation was detected from the stationary disk, whether the open or closed part of the disk faced the bolometer; but unfortunately this test was not made for the moving disk. The disk with the 240° opening gave values 0.5 per cent too high (see table IX). The results with the 120° disk (6 openings of 20° each) were in still greater error. The space between the bolometer and the shield was then entirely inclosed, and with the disk close to the opening (7×10 cm.) in the shield the discrepancy became still greater. It was then found that the increased transmission is due to the moving disk and depended upon the distance of the disk from the screen.

It was further shown that the transmission was proportional to the speed, so that the 240° disk (true transmission 66.827 per cent[1]) gave

[1] These disks and their constants were supplied by Dr. Hyde. Bureau of Standards, Bulletin, 2, p. 1, 1906.

values from 69.3 to 77.2 per cent. In fig. 105 are plotted the galvanometer deflections for different distances of the disk (abscissæ) from the screen. The latter was 80 cm. (source at 2 m.) from the bolometer, and had an opening in it which was the size of the openings in the sectored disk. No radiation was observed from the stationary disk, nor from the shields back of it when the open sector was before the bolometer. The speed of the disk was such as is used in photometry, and was kept constant for each series of observations. In the lower curve for the 240° disk the speed was slow and there was a flicker on viewing it. The curves show that the maximum radiation occurs when the disk is about 6 cm. from the shield; and it disappears immediately on stopping the disk.

TABLE IX.—RELIABILITY OF BOLOMETER MEASUREMENTS.

Direct deflection. *a*	Deflection with disk. *a*	Ratio.	Direct deflection. *a*	Deflection with disk. *a*	Ratio.
Disk opening, 240° = 66.827.			Disk opening, 120° = 33.406.		
9.42 cm.	6.33 cm.	*b* 67.23	15.82	5.65	*e* 35.70
9.35	6.28	*b* 67.25	11.56	4.14	*f* 35.75
11.82	7.95	*b* 67.25	12.31	4.28	*g* 34.8
9.11	6.12	*b* 67.2	30.40	10.53	*h* 34.7
8.94	6.04	*c* 67.5	13.75	4.70	*i* 34.5
13.31	8.99	*c* 67.6	14.15	4.75	33.56
Disk opening, 180° = 50.125.			17.04	5.68	33.38
17.17 cm.	8.65	*d* 50.37			
17.21	8.64	*d* 50.20			

a Mean of 6 to 10 readings.

b Galvanometer period 8 seconds, vibration undamped; 20 ohms in series with galvanometer. Temperature sensitiveness = $6° \times 10^{-6}$ C. High values due to radiation from moving disk, which is 0.5 m. from screen.

c Galvanometer period 14 seconds and vibration just damped. Temperature sensitiveness = $1°.2 \times 10^{-6}$ C.

d Nernst heater on 98 volts at 1 m. from bolometer. Galvanometer period 8 seconds. 30 ohms in series with galvanometer. Total deflection about 80 cm. Individual deflections vary 0.2 to 0.5 per cent from mean.

e Galvanometer period 14 seconds.

f Galvanometer period 8 seconds. Disk better shielded than in previous experiments and closer to screen—6 cm. from it. Heater 150 cm. from bolometer; screen at 80 cm.

g 14 ohms in galvanometer circuit. Galvanometer period 14 seconds. Nernst heater on 74 volts.

h No resistance in galvanometer circuit; results show that high value is not due to lack of proportionality of galvanometer deflections.

i Nernst heater on 95 volts. 20 ohms in galvanometer circuit. Total deflection about 45 cm.

The motor was run continuously for a complete series of measurements and no deflections greater than 1 to 2 mm. were observed from it or the disk, immediately after stopping the rotation. In these tests the motor was shielded from the bolometer. On removing the shield and the disk and on running the motor the deflections were from 1 to 3 mm. The whole shows that the sectored disk is not as applicable as one would suppose, unless one determines the corrections which in two series of experiments were found to be in very close agreement.[1] In the present curves

[1] The sector was rotated at a higher speed than actually required with a bolometer. By means of suitable pulleys the speed may be reduced to perhaps $\frac{1}{30}$ that used in the present test, which would decrease the errors.

the galvanometer was at its full sensitiveness — no resistance in series — so that in the actual experiments (table IX) the error was less exaggerated. For the 240° disk where the error in the deflections was only 1 or 2 mm. the correction reduces the observed values close to the true one.

From the consistency of the ratios in each series, which is of the order of 0.2 to 0.3 per cent, it will be noticed that the bolometer is a very reliable instrument in spite of its mechanical weakness.

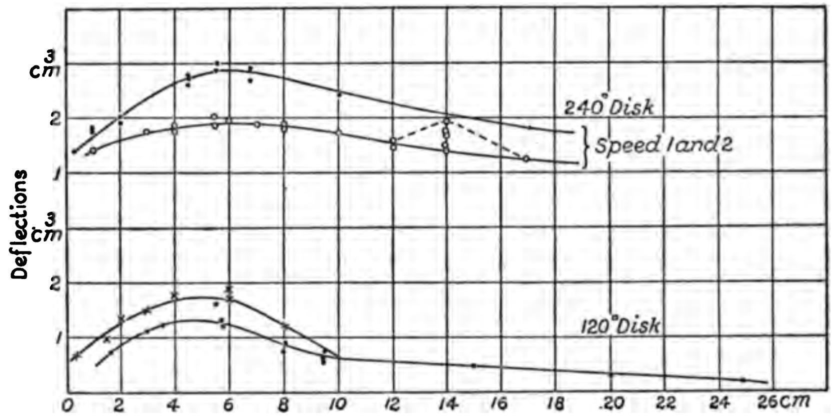


Fig. 105. — Radiation due to rotating sectored disk.

VI. SUMMARY.

The present paper deals with four instruments for measuring radiant energy, viz, the radiomicrometer, the linear thermopile, the radiometer, and the bolometer with its auxiliary galvanometer.

As a result of this historical inquiry and by experiment it was shown that the radiomicrometer is capable of great improvement, by reducing its weight, by lengthening its period, and by placing it in a vacuum. It was further shown that on account of para- and dia-magnetism the sensitiveness of the radiomicrometer is very limited, perhaps only a fifth of the best bolometers described.

It was also shown that the Rubens thermopile is as sensitive as the best bolometer, and that its heat capacity can be greatly reduced by using thinner (0.06 to 0.08 mm. diameter) wires, which are made shorter, thus keeping the resistance low. The computed errors due to the Peltier effect are about 1 part in 300. The thermopile is not so well adapted as is the bolometer for instantaneous registration of radiant energy and it does not admit so great a range in variation of sensibility; but, on account of its greater steadiness, it commends itself for measuring very weak sources of radiation, *e.g.*, the extreme ultra-violet and infra-red region of the spectrum.

By a direct comparison it was shown that the radiometer can be made just as sensitive as the bolometer, but its period will be much longer. It

was found that the radiometer is not selective in its action, and, hence, that it can be used for measuring ultra-violet radiation. The main objection to the use of a radiometer is its long period; but, since it is easily shielded from temperature changes, and since it is not subject to magnetic perturbations, this long period is of minor importance so long as we are dealing with a constant source of radiation. In spectrum energy work its usefulness is limited to the region in which the window is transparent — to 20 μ and from 40 to 60 μ by using quartz. The fact that the deflections of the radiometer can not be obtained in absolute measure is a minor objection, since in but few cases (thus far at least) has it been necessary to thus obtain the deflections. The action of a radiometer is somewhat analogous to a photographic plate, in that it will detect weak radiation, provided one can wait for it, and, on account of its great steadiness, is, of all the instruments considered, probably the best adapted in searching for infra-red fluorescence.

A bolometer installation is so distributed that it is difficult to shield from temperature changes. In spite of its small heat capacity the bolometer has a "drift" due to a slow and unequal warming of the strips. Air-currents which result from the hot bolometer strips also cause a variation in the deflections of the auxiliary galvanometer. Nevertheless, despite these defects it is the quickest acting of the four instruments considered, and is the best adapted for registering the energy radiated from a rapidly changing source. For precision work it is necessary to keep the bolometer balanced to less than 1 cm. deflection.

The auxiliary galvanometer is the main source of weakness in measuring radiant energy, and in places subject to great magnetic perturbations a period greater than 5 seconds, single swing is to be avoided. Hence, although a greater sensitiveness is possible, the working sensibility of the various galvanometers studied is of the order of $i=2\times10^{-10}$ ampere per millimeter deflection on a scale at 1 m. Under these conditions the various bolometers used were (as a fair estimate of the recorded data) sensitive to a temperature difference of $4^\circ\times10^{-5}$ to $5^\circ\times10^{-6}$ per mm. deflection, on a scale of 1 m. The galvanometer sensibility was found to be closely proportional to the period.

A direct comparison of the thermopile and the bolometer shows that there is little preference, other than a personal one, in these two instruments.

The use of a rotating sectored disk for reducing the intensity of the source is liable to introduce errors, which must be taken into account.

APPENDIX III.

ADDITIONAL DATA ON SELECTIVE REFLECTION AS A FUNCTION OF THE ATOMIC WEIGHT OF THE BASE.

As this work goes to press the experiments of Morse[1] have been published, and since it contains considerable new data for the region of the spectrum from 10 to 15 μ, it is included here for the sake of completeness.

In that paper considerable comment is made upon the fact that the writer (see Carnegie Publication No. 65) missed the reflection bands in calcite and in magnesite, previously found by Aschkinass at 11 to 12 μ. In reply it may be stated that these two substances were examined in the preliminary work on reflection spectra, in order to get a check on the calibration; and, on finding the reflected energy very weak, no attempt was made to locate the bands known to be at 11 to 12 μ. In this work a Rubens thermopile (heavy wires) was used, which was sluggish and was disturbed by air-currents. Although the sensibility was higher than in the radiometer previously used, the small deflections were not so reliable and no attempt was made to locate weak reflection bands beyond 11 μ, such as are found in the carbonates. This demonstrates the superiority of the radiometer for measuring weak radiation.

The investigation of weak reflection spectra in the extreme infra-red is accomplished under great difficulties, and Morse has done an excellent service in obtaining data in this region of the spectrum. He used a 35 cm. focal length mirror spectrometer as compared with the writer's 52 cm. focal length mirrors. In the larger spectrometer the energy in the spectrum is much weaker, while the resolution is greater. The shorter focus does not militate against the results, however, which show that the simple atomic weight relation among the carbonates found by the writer at 6 to 8 μ holds for the long wave-lengths at 11 to 15 μ, where the dispersion is considerably greater. The writer found the reflection band of the carbonates at 6 μ very complex (see Chapter III) and it would be interesting to learn whether the bands at 11.4 to 15 μ are likewise. In table X are given the maxima of the reflection bands of the carbonates examined by Morse. It contains one new substance, $MnCO_3$, not examined by the writer. The values of the maxima of the first band are not always in agreement, but this appears to be due to the difference in resolving power of the two instruments. In fig. 43 are plotted the wave-lengths of the

[1] L. B. Morse: Astrophys. Jour., 26, p. 225, 1907.

reflection maxima of the bands at 11.5 and 14.5 μ against the atomic weight of the base. From this it will be seen that the rate of shift of the band with increase in atomic weight of the base is greater for the bands at 11.5 and 14.5 μ than for those at 6.6 and 7.0 μ, just as was found for the bands of the sulphates at 4.6 μ, at 6.2 to 6.6 μ, and at 8.2 to 9.3 μ (see figs. 44 and 45).

TABLE X.

Substance.	Chemical composition.	Atomic weight of base.	Reflection maxima.		
			Band 1.	Band 2.	Band 3.
Magnesite	$MgCO_3$	24.2	6.5 μ	11.2 μ	13.9 μ
Calcite	$CaCO_3$	39.7	6.6	11.31	14.2
Aragonite................	$CaCO_3$	39.7	6.65	11.55	14.2
Rhodochrosite............	$MnCO_3$	54.6	6.63	11.47+	14.0−
Siderite	$FeCO_3$	55.5	6.60	11.47−	13.9−
Smithsonite	$ZnCO_3$	64.9	6.7	11.38	13.6
Strontianite	$SrCO_3$	86.9	6.76	11.56	14.37
Witherite	$BaCO_3$	136.4	6.86	11.60	14.5
Cerussite	$PbCO_3$	205.4	7.2	11.94	14.8

By arbitrarily selecting KNO_3 and $AgNO_3$ from the nitrates, Morse found the line drawn through the maxima of the reflection bands was "approximately parallel" to those of the carbonates (see fig. 43). Moreover, the line drawn through the maxima of the sulphates, at 8.6 to 9 μ, is also closely parallel with those of the carbonates. From this he was led to suspect that the shift of the band with increase in the atomic weight of the base is of the same order of magnitude in carbonates, nitrates, and sulphates. If the data had been plotted to a larger scale, as the accuracy of the values of the maxima seem to permit, then the lines would not even be approximately parallel, as will be noticed in figs. 43 and 44.

After examining the reflection and transmission spectra, one or both, of over 300 substances, the observations lying in the region of the spectrum from 0.5 to 30+ μ, I have found that it is an easy matter to work out all sorts of fantastic relations, only to learn, after gathering more data, that the whole thing was an illusion. For this reason it seems to me that the linear relation between the weight of the element, combined with equal amounts of oxygen in the acid radical found by Morse by arbitrarily selecting maxima of reflection bands, is misleading. From the earliest work of Abney and Festing to the latest (theoretical) work of Einstein, it has been generally accepted that oxygen is the active element in causing (at least in "sharpening") certain bands, just as sulphur has been found quite inactive. The great groups of chemically related compounds have been found to have similar absorption and reflection spectra, but no simple relation could be established between the spectra of the groups of compounds. The present simple relation results from selecting particular reflection bands found in certain carbonates, nitrates, sulphates, and sili-

cates. Hence, the selection of KNO_3 (max. at 7.1 μ) from the nitrates by Morse seems arbitrary, for Pfund (*loc. cit.*, see Carnegie Publication No. 65) has given a large number of nitrates which have a band in common at 7.45 μ. This seems to be a characteristic band of the nitrates, and $AgNO_3$ might have been selected instead of KNO_3. A characteristic band of the sulphates appears to be at 9.1 μ (harmonic with the one at 4.55 μ), while Morse selected a less frequent one at 8.6 μ. From the silicates, $MgSiO_3$, with an insignificant band at 9.1 μ, was selected, while Na_2SiO_3, with a sharper band at 9.9 μ, and Zn_2SiO_4, with a group of still more intense bands at 10.1, 10.6, and 11 μ, respectively, were not considered.

In $PbMO_4$ the maxima lie in the region of 11.75 and 13 μ, while in $CaWO_4$ there is a large reflection band with maxima at about 11.4, 11.9, and 12.5 μ, respectively. These data including Morse's are plotted in fig. 106 and tabulated in table XI, from which it will be observed that

TABLE XI.

Substance.	Chemical formula.	Atomic weight of base.	Weight with 48 gr. of O.	Position of band.
Calcite................	$CaCO_3$	39.7	12 gr. of C	6.6 μ
Potassium Nitrate	KNO_3	38.9	14 gr. of N	7.15 (7.05)
Anhydrite	$CaSO_4$	39.7	24 gr. of S	8.6
Enstatite	$MgSiO_3$	24.2	28 gr. of Si	9.1
Zircon	$ZrSiO_4$	90.6	28 gr. of Si	10, 10.6, 11 μ
Wulfenite	$PbMoO_4$	206.9	72 gr. of M	11.75, 13
Scheelite	$CaWO_4$	39.7	138 gr. of W	11.4, 11.9, 12.5

the graph is not a straight line, and that if any relation exists it is a very complex curve, showing that for the region up to 10 μ the atomic weight of the element in the acid radical has a great effect in shifting the maximum, while beyond this point the atomic weight of the element united with oxygen is of minor importance. In fact, the base and the element united with the oxygen in the acid radical seem to influence each other.

As an illustration of the arbitrariness in selecting bands to establish relations like the aforesaid, calcite ($CaCO_3$) may be noticed, in which the reflection band is complex with maxima at 6.4 (?), 6.5, 6.6, and 7 μ, while in its isomer, aragonite, the maxima are at 6.4 (?), 6.52, 6.74, and 7 (?) μ. In $SrCO_3$ the band with a maximum at 6.67 μ could not be resolved even with a fluorite prism. Hence, one is at a loss to know which band (at 6 to 7 μ) to select from the carbonates to compare with the sulphates, nitrates, and silicates. On the other hand, in the carbonates and in the sulphates the maxima of the bands have been plotted in their order of occurrence, which would seem to eliminate personal bias in the selection of maxima. From this it would appear that the simple, linear relation between the atomic weight of the base and the maxima of the reflection

bands in the carbonates and in the sulphates is in agreement, at least as a first approximation. Even with these data at hand, speculation in regard to dynamical relations among atoms in the molecules had better be postponed until more data have been procured.

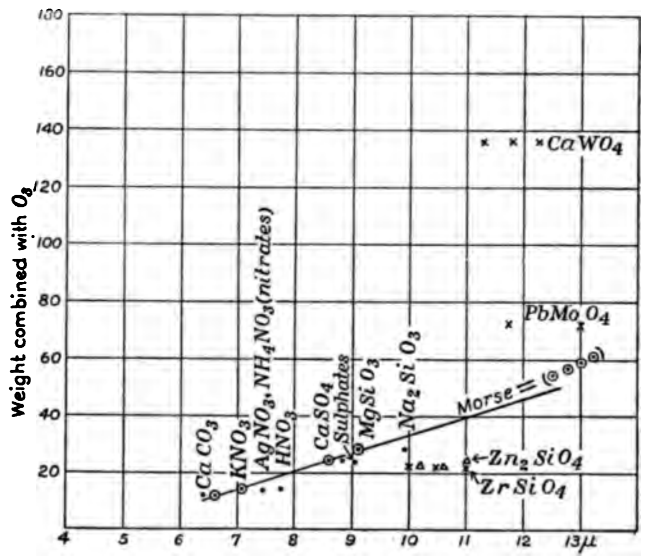


FIG. 106. — Maxima of reflection bands.

The data on the reflection bands of the carbonates at 11 to 15 μ is of interest in connection with the question of the value of the extinction coefficient necessary to give rise to selective reflection. In Carnegie Publication No. 65, page 70, is given the transmission band of a thin section of calcite, from which it will be observed that the absorption band at 11.4 μ coincides with the band found by reflection. It would seem desirable to examine the transmission of thin sections of carbonates in this region of the spectrum, using polarized energy, to compare with the intensity of the bands found by reflection. The reflection bands at 14 μ were frequently found to be extremely weak, and in view of the importance of the bearing of the results upon the whole subject, it seems highly desirable to examine the transmission spectra of thin sections of these minerals (using preferably polarized energy), to verify the aforesaid observations. (See foot note on page 30.)

ADDENDUM.

Mr. Morse has recently presented "Additional observations on the selective reflection of salts of oxygen acids" (Washington meeting, American Physical Society, April, 1908). He chose substances in which the "weight of the acid-forming element is not greater than the weight of the oxygen with which it is combined." These substances are: $CaCO_3$ with a reflection maximum at 6.6 μ; KNO_3 at 7.1 μ; $AgNO_3$ at 8 μ; $CaSO_4$ at 8.6 μ; $KClO_4$ at 9 μ; $CaSiO_3$ at 9.2 μ; $KClO_3$ at 9.9 μ; $KMnO_4$ at 10.9 μ; $PbCrO_4$ at 11.5 μ; and $CaTiO_3$ at 14.2 μ. These maxima lie close to the line drawn through them, when plotted against the weight of the oxygen. He excluded $PbMO_4$, $CaWO_4$, etc., because the weight of the acid-forming element is greater than that of the oxygen present. Of course, if we admit the validity of such a procedure the rule is proven; but a rule loaded down with exceptions can not prove satisfactory, and much as all spectroscopists wish to establish such a simple relation ***between spectra of different groups of compounds***, it should be along lines of less arbitrary elimination.

On the other hand, this simple atomic-weight relation seems to hold *for substances belonging to the same group of compounds*, even for remote parts of the infra-red spectrum, as was shown by Nichols and Day (Washington meeting, American Physical Society, April, 1908). They found a band of residual rays in $SrCO_3$ at 43.2 μ and in $BaCO_3$ at 46.5 μ, for the carbonates (see fig. 45).

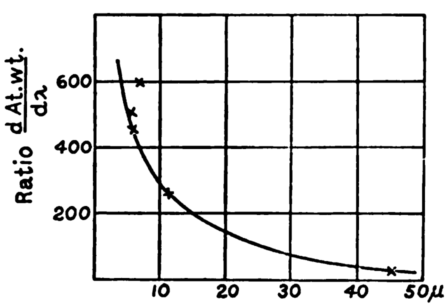


FIG. 107. — Mean position of groups of residual rays.

If we take the ratio of the increase in atomic weight of the base to the position of the maximum, as read from the graphs in figs. 43 to 45, the value for the group of bands at 6.5 μ is about 500 to 1, at 11.5 μ it is 260 to 1, and at 45 μ it is 20 to 1. The graph (fig. 107) of these values appears to be an hyperbola. If such a relation really exists and if the carbonates have a band in the region of 30 μ, corresponding to the $CaCO_3$ and $MgCO_3$ bands, then the aforesaid ratio of atomic weight to position of the maximum is about 90 to 1, and one would expect to find a maximum for $PbCO_3$ at 31.5 μ and $SrCO_3$ at 30 μ. However, from the variation in complexity of the bands at 6 to 7 μ and in intensity of the bands at 11 to 14 μ, it is evident that it is use-

less to attempt to predict their behavior in the remote infra-red. On the whole, the present data indicate that the greater the wave-length of the maximum the greater the shift of that maximum with increase in atomic weight of the base.

The latest conclusion (Morse, Phys. Rev. 26, p. 526, 1908) is that "present data do not form any reasonable basis for assuming that all the reflection bands in even the simpler oxygen acids are connected with each other by such a simple relation as that found to hold roughly for the first bands, and which may be found to hold also for the second bands in the salts examined."

INDEX OF SUBSTANCES.

The Topography of the Chlorophyll Apparatus in Desert Plants.

BY

WILLIAM AUSTIN CANNON.

The Induction, Development, and Heritability of Fasciations.

BY

ALICE ADELAIDE KNOX.

WASHINGTON, D. C.
PUBLISHED BY THE CARNEGIE INSTITUTION OF WASHINGTON.
1908.

CARNEGIE INSTITUTION OF WASHINGTON

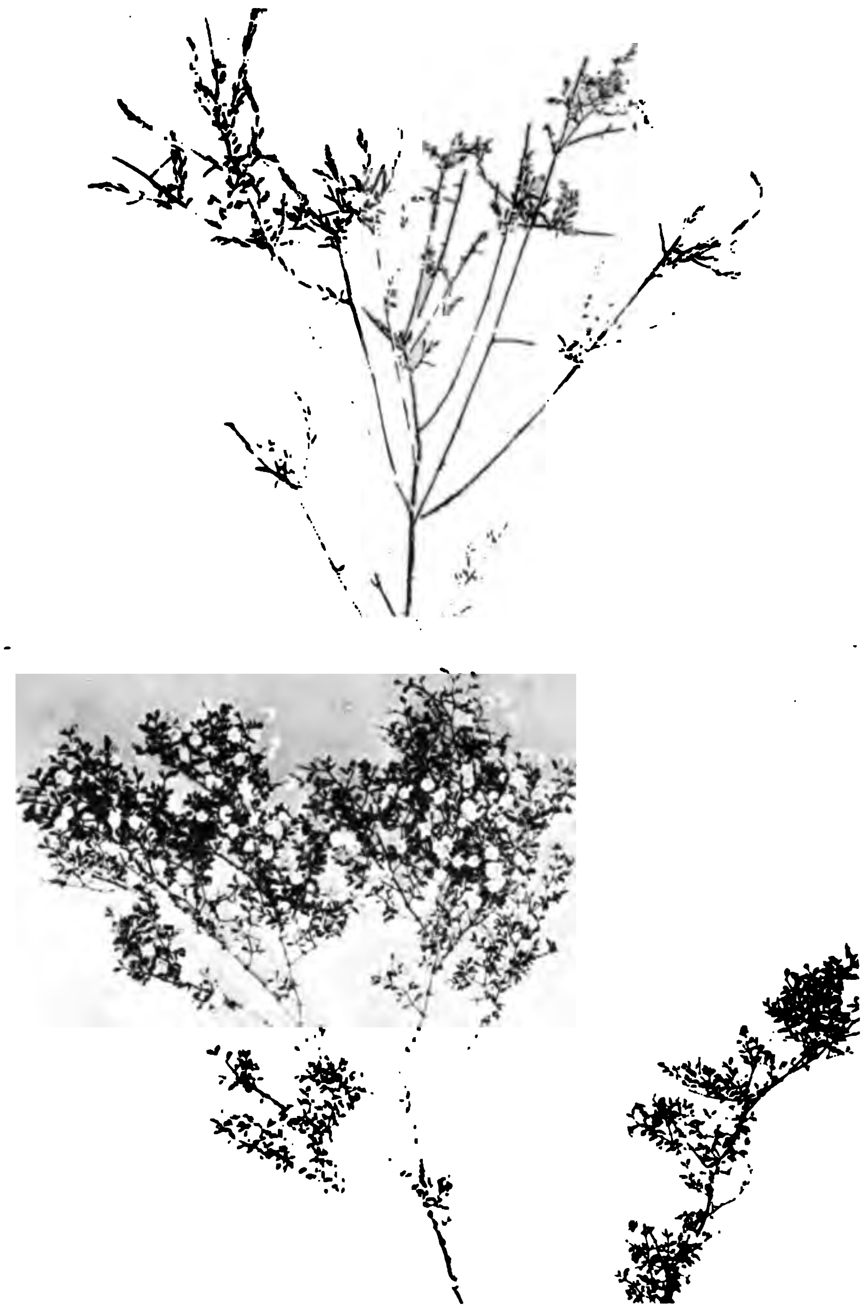
PUBLICATION No. 98

THE CORNMAN PRINTING CO.,
CARLISLE, PA.

The Topography of the Chlorophyll Apparatus in Desert Plants.

BY

WILLIAM AUSTIN CANNON.



A.—KRAMERIA CANESCENS. Branch from a plant which is growing on the slope at the northern base of the Tumamoc Hill. This is a plant with the deciduous habit. April 25, 1907.

B.—COVILLEA TRIDENTATA. Branch in fruit of a plant which is growing near the laboratory building. This is an evergreen. April 25, 1907.

THE TOPOGRAPHY OF THE CHLOROPYHLL APPARATUS IN DESERT PLANTS.

ENVIRONMENTAL CONDITIONS IN RELATION TO STRUCTURE.

The plants which come under observation in this paper are fairly representative of the perennials of the Tucson region (2000 to 3000 feet), with an average rainfall of 12 inches, and occur in a comparatively wide range of habitats. These include the bottom-lands of the Santa Cruz River which are bordering upon the Laboratorv domain; low desert mountains, Tumamoc Hill (a portion of the Laboratory domain); the lower slopes and washes of Tumamoc Hill; dry, low ridges, the so-called aerial mountain-deltas, which lead eastward from the main range of the Tucson Mountains; the broad and gently rolling mesa or table-land; and, finally, the bed of the Santa Cruz River and certain contiguous irrigating channels and roadside ditches.

In these habitats a relatively large range of environmental conditions are encountered. In them there is a wide variety of soils, of drainage conditions, and of exposure to light and to air-currents. The bottom-lands are characteristically deep and are made up largely of a clay or loam, with strata of sand some distance beneath the surface. Toward the sides of the bottom-lands the top-soil becomes more or less sandy or gravelly, with the coarser material on the slopes immediately above and leading out of the bottoms. Then comes either the mesa with its thin layer of top-soil and a nearly impervious hardpan underlying it, or the lower slopes of the desert mountains, with coarse rock and bowlders and bed-rock, clayish soil, more perfect drainage, and various exposures.

The water-table of the river-bottom lies from 6 to 12 m. from the surface of the soil; that of the mesa is frequently 25 m. and deeper beneath the surface. The location of the reservoirs of water on the mountain have not been determined, but are possibly connected with the fissures and the pockets in the rocks.

Very curiously the leaf-habit of these desert forms, and even their general xerophytic character, are not consistently associated with the character of the habitat. This will be apparent from a few examples. The evergreen habit is not correlated with the conditions of water-supply, or at least with the only sure water-supply—that of the river-bottoms. Of the plants studied in connection with this paper which do not drop their leaves with change of

seasons, *Covillea tridentata* (plate 1, B) and *Celtis pallida* (plate 2, B), the former grows on the mesa and the latter on the slopes of the mountain. Also what is outwardly and palpably the most extreme type of xerophyte, *Kœberlinia spinosa* (plate 3, A) having leaves only when in the seedling stage, which is provided with palisade chlorenchyma, a very heavy epidermis, and with deeply sunken stomata, appears most frequently, perhaps, in places where the soil is quite deep. In other words, this form avoids the driest situations. Other forms which are leafless in dry times and therefore the most of the year, as *Baccharis emoryi* (and perhaps *Aster spinosus* should be included, although it has annual subaerial parts), and have xerophytic structure, are to be found only along the river-beds or where the water conditions are most favorable. Cacti, however, are usually found in dry situations. This is probably associated with their habit of treasuring the scant amount of water as it comes to them from the rains, in place of depending on subirrigation, as in the other forms given. *Prosopis*, which has a constant as well as abundant water-supply, forms and sheds its leaves with the advent and passing of the seasons in a manner usually and perhaps always quite independent of the time or the amount of the rainfall. Certain of the more gross characters of these desert plants are thus scarcely to be attributed to the molding influences of the environment; it will doubtless be necessary to take into consideration the peculiar history of each plant, its gradual modification from its remote mesophytic ancestor, before habits and structure are satisfactorily related.

As is well known, a leading feature of the morphology of desert perennials is the reduction of the transpiring surface. Plants may be wholly without leaves, or leaves may be present during early growth or during favorable seasons only, or if leaves are a feature they may be much reduced in size (plate 4). In the former instances the twigs and the branches assume the functions of leaves; in the last case it will be shown in this paper that the same is also true when leaves are present but reduced in size or present during favoring seasons only.

Among other characters which distinguish the leaves of xerophytes is the palisade nature of at least the subepidermal portion of the chlorenchyma. That is, the chlorophyll tissues of the leaf are to a greater or less extent composed of cells whose long axes are placed at right angles to the surface of the leaf. It is of interest, therefore, to learn how far the structure characteristic of the leaves is found in such stems as exercise the function of leaves.

To anticipate one of the findings of this paper, in plants whose transpiring surface is most perfectly reduced the chlorenchyma of the stem is in certain regards very like that in the leaf of the same species; but in those with a more or less pronounced leaf-surface the chlorenchyma of the stem is unlike that of the leaf. In the former case the stem structure is palisade; in the

latter it is spongy. The immediate reason for this variation is not clear. The environmental conditions of the two classes of plants may be, as far as one can determine, quite the same. The cause of this must evidently be looked for elsewhere and, as will be shown below, may perhaps be associated with the character of the structures exterior to the chlorenchyma.

A noticeable feature of many of the desert plants as opposed to those of the humid regions—a feature very conceivably related to the distribution of chlorophyll in the stems—is the open character or, in a measure, the looseness of growth. This is characteristic of both trees and shrubs. Among the shrubs this appearance is due in part to the relatively small number of branches and in part to the small size of the leaves. Quite likely the latter is the leading reason in either trees or shrubs. As a result, all portions of the plant are exposed either to direct sunlight or to very strong illumination at all times during the day. The light conditions are such in consequence that wherever chlorophyll is to be found, even in the oldest parts, as it is in *Parkinsonia*, photosynthesis can take place.

On the other hand, the various positions attained by the branches as related to the incident rays of light insure a certain degree of protection from the most intense light, as is found in such plants as *Smilax*, of the Florida scrubs, for example, by the erect posture of the leaves.

In considering the affinities of the plants which have been under observation and their distribution, it is of interest to note that their nearest relatives are desert forms. As one result of this fact, the possibility of comparing congeners growing in desert and in humid regions is in many cases precluded and one important source of evidence as to the direct origin of these plants is thrown out. Those plants which are confined to North or South America include *Baccharis*, *Cereus*, *Condalia*, *Covillea*, *Franseria*, *Krameria*, *Fouquieria*, *Kœberlinia*, and *Olneya*, which occur in the arid regions of North America only. *Ephedra*, *Prosopis*, and *Zizyphus* have nearly worldwide distribution, since they occur both in the Old and the New Worlds and in both hemispheres, but not in colder regions. *Celtis* is the only marked exception and has representatives in cold temperate and humid regions, as well as in the warm and dry regions, and is practically cosmopolitan in distribution.

SCOPE AND PURPOSE.

tudies on the transpiration of desert plants when in a leafless con-
ither as a result of the usual seasonal changes, the advent of
or normally without leaves, lead to the discovery that with deli-
aratus* the evolution of watery vapor can be demonstrated when
be least expected and in surprisingly large amounts. Some of the
thus studied were *Cereus giganteus*, *Echinocactus wislizeni*, *Fouquieria*
ens, *Kœberlinia spinosa*, *Opuntia versicolor*, *Parkinsonia microphylla*,
ers.† This work early suggested an examination into the extent of
ll and the character of the chlorophyll-bearing tissues in the con-
its plants. As opportunity offered the work was carried on,
ated so much of interest that a summary was presented before
iety of America, New Orleans, December, 1905.

ory study of the chlorophyll relations of the desert plants
into account the peculiar light conditions to which they are ever
In the present study no attempt has been made to do this, in part
e complexity of the subject, in part because of the lack of sat-
uments for making light measurements. It therefore has
an observation of the chlorophyll apparatus as it exists,
ce to correlations other than the obvious biological ones
u up everywhere throughout the entire course of the work.

ODS AND MATERIAL.

esea present one living material at hand is a prime
for , which are very obvious, that chlorophyll can be
fac identified in living material, and, furthermore, a large
of material is a necessity from which to select what is representative as well as by which to know the range in variation of the structures to be studied.

While unusual conditions have been taken into account, this paper aims to present primarily the usual and normal condition of the chlorophyll apparatus. In every instance conclusions were drawn from the study of only normal and healthy plants, and with but one exception (*Parkinsonia aculeata*) the plants were studied in their proper habitats.

The developmental method of study was employed. That is to say, vigorous branches or stems were selected and sections were made at measured intervals from the tip. Whenever necessary, comparative observations, in addition, were made on mature structures, so that in each instance the story might be as complete as possible. The presence of chlorophyll in a stem

*Cannon, W. A.: A new method of measuring the transpiration of plants in place. Bull. Torr. Bot. Club, 1905, **32** : 515.

†Cannon, W. A.: On the transpiration of *Fouquierias plendens*, Bull. Torr. Bot. Club, 1905, **32** : 397; and Biological relations of certain Cacti, The American Naturalist, 1906, **40** : 27.

was determined by inspection only, and all chloroplastids that from comparison were seen to be normally colored were classed as being functional and were considered as having adequate amounts of light and of air.

The following plants were passed under observation during the course of this study: *Aster spinosus* Benth.; *Baccharis emoryi* Gray; *Celtis pallida* Torr.; *Cereus giganteus* Englm.; *Condalia spathulaca* Gray; *Covillea tridentata* Vail; *Ephedra antisyphilitica* C. A. Meyer; *Fouquieria splendens* Englm.; *Franseria dumosa* Gray; *Kœberlinia spinosa* Zucc.; *Krameria canescens* Gray; *Olneya tesota* Gray; *Parkinsonia aculeata* L.; *Parkinsonia microphylla* Torr.; *Parkinsonia torreyana* Watson; *Prosopis velutina* Wooton; *Salix nigra* Marsh.; *Sambucus mexicana* Presl.; *Zizyphus parryi* Torr.

SPECIAL PART: THE CHLOROPHYLL APPARATUS.

Aster spinosus; Baccharis emoryi. (Fig. 1.)

These plants inhabit the wash along the river and the irrigating and wayside ditches, where water is frequently to be found. *Aster spinosus* is an annual with perennial root; *Baccharis emoryi* is perennial. Both *Aster* and *Baccharis* are usually devoid of leaves, but the young portions at least are supplied with rudimentary ones.

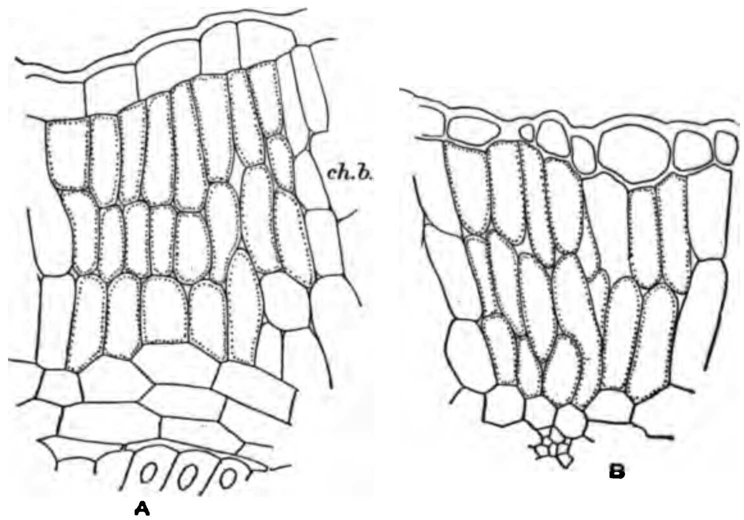


Fig. 1.—*Baccharis emoryi: A*, segment from transverse section of young stem to show the character of cortical chlorophyll band (*ch. b.*); *B*, section of leaf, magnified as in *A*.*

Chlorophyll of the stem is confined to the cortex in both species and in both the chlorenchyma is palisade. The palisade in the stems of each also closely resembles that in the rudimentary leaves of the same species. This similarity in the structure of the chlorophyll band* in the stem and of the

*In all figures chlorophyll is indicated by stippling.

chlorenchyma of the leaf was observed also in *Krameria canescens*, where the cortical chlorophyll band is likewise palisade.

CELTIS PALLIDA. (Plate 2, B, and figs. 2 and 3.)

The specimen of *Celtis* which was chosen for study is growing in the arroyo below and to the east of the Laboratory building. A branch about 2 m. in length was selected and sections made at the following distances from the tip: 6, 21, 34, 49, 64, 79, 144, and 178 cm. The parts of the branch where the sections were made had the following diameters: 2, 3.5, 4, 4.5, 6, 8, 8.5 mm. and 1 and 1.6 cm., respectively. A section of a branch 2 mm. in diameter and 6 cm. from the tip shows the following general structural relations:

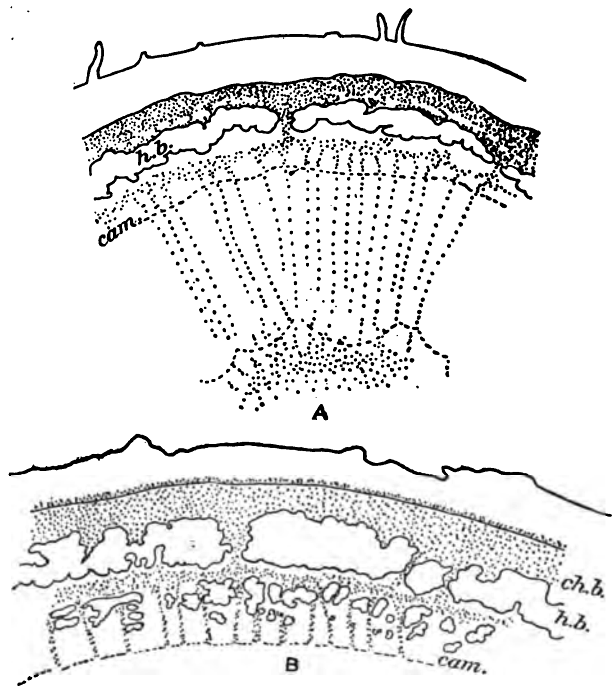


FIG. 2.—*Celtis pallida: A*, section of branch 2 mm. in diameter; *B*, section of branch 3.5 mm. in diameter.

Cortex: There are several well-defined cortical divisions. An epidermis with a thin outer wall and a subepidermal tissue about three cells in thickness bound the stem. Within this lies a chlorophyll band which is also about three cells in thickness. A discontinuous ring of hard bast is situated within the chlorophyll band. Between the hard bast and the cambium is the region of the inner cortical parenchyma.

Woody cylinder: The wood is composed very largely of wood fibers with a noticeably small amount of wood parenchyma. The pith is well marked but does not need further mention in this connection.

Chlorophyll occurs in the outer cortical parenchyma, in much of the parenchyma which lies between the hard bast and the wood, in the medullary rays, both of wood and of cortex, and in the outer cells of the pith.

* The term *chlorophyll band* as used in this paper refers to that portion of the cortical parenchyma that lies between the epidermis and the ring of mechanical tissue which is about midway between the epidermis and the cambium. It is the largest and the most enduring chlorophyll tissue in the stem.

A

B

A.—CONDALIA SPATHULACA. Branch from a plant, which is an evergreen, growing on the rocks below and to the north of the laboratory building. April 25, 1907.

B.—CELTIS PALLIDA. Portion of a branch from a plant which is growing near the Condalia of "A," showing the character of the leaf-covering. This also is an evergreen.

With an increase in diameter of the stem characteristic changes take place, more particularly in the cortex, which greatly affect the topography of the chlorophyll apparatus. As the cortex becomes wider, rings of secondary hard bast are formed within the primary ring; parenchyma, which for the most part contains chlorophyll, extends between these rings. The groups of bast are connected in part or always by medullary rays. As the stem increases in diameter these groups are pushed farther and farther apart and the intervening portion becomes filled with parenchyma which contains chlorophyll. In this respect *Celtis* strikingly resembles *Prosopis*. The secondary hard bast of the former, however, is not placed as regularly as in *Prosopis*, and the chlorophyll distribution, consequently, of *Celtis* is not so symmetrical as in the other species.

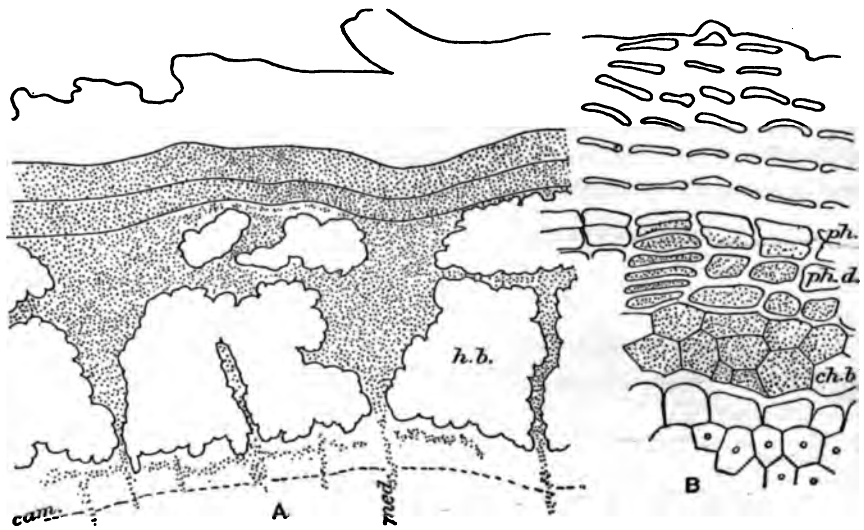


FIG. 3.—*Celtis pallida: A*, section of branch 4.5 mm. in diameter; *B*, detail of *A*, showing presence of chlorophyll in secondary cortex; *cam.*, cambium; *ch. b.*, cortical band of chlorophyll; *h. b.*, hard bast; *med.*, medullary ray; *ph.*, phellogen; *ph. d*, phelloderm.

But the greatest change in the chlorophyll apparatus occurs as a result of the formation of phelloderm. The cork-cambium arises in the cells immediately outside the chlorophyll band and by its activity gives rise to periderm without and phelloderm within. The latter contains chlorophyll. When the amount of phelloderm about equals the thickness of the chlorophyll band no more appears to be formed. The result is that the chlorophyll band of stems from 4 mm. to 1.6 cm. in diameter is about half phelloderm. How this relation is in older stems was not learned.

How long the chlorophyll remains active in the stem was not determined. It is present in the outer portions of the pith in the stems 8.5 mm. diameter after it has disappeared from the medullary rays, but whether this is a con-

stant relation was not learned. In a branch 1.6 cm. in diameter, as well as one 1 cm. in diameter, the chlorophyll was confined to the cortex.

The following measurements were made:

Distance of section from tip.	Diameter of stem.	Width of cortex.	Depth of phelloderm.	Width of phelloderm.	Depth of chlorophyll band.	Width of chlorophyll band.
cm.	mm.	μ	μ	μ	μ	μ
6	2	......	......	......	78	41.6
21	3.5	320	......	......	96	25.6
34	4	300	54.4	39.2	89.6	28.8
49	4.5	415	80	22.4	102.4	22.4
64	6	547.8	80	32	102	32
79	8	547.8	76.8	19.2	96	35.2
144	10	581	80	28	108.8	25.6
178	16	1079	118.4	28.8	147.2	32

CONDALIA SPATHULACA. (Plate 2, A, and fig. 4.)

ant from which the branch studied was taken is growing by the Road near the northeast corner of the Laboratory domain. The about 1.5 m. high and is a very vigorous one.

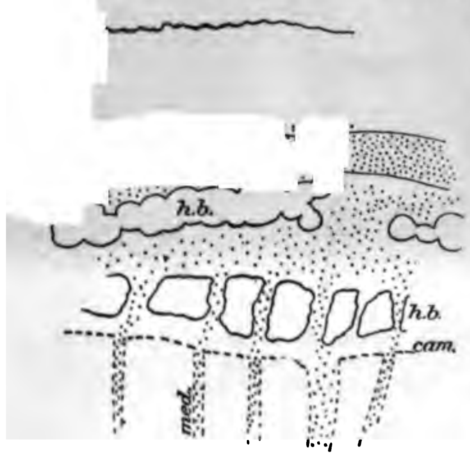


FIG. 4.—*Condalia spathulaca:* Section from a branch 2 mm. in diameter.

Sections were made at the following distances from the tip: 2, 5, 20, 35, 65, 95 cm. These were 1.5, 2, 4, 7.5 mm. and 1.2, 1.7 cm. in diameter, respectively.

A cross-section of a young branch 1.5 mm. in diameter and 2 cm. from the tip shows the following leading structural characters: An epidermis with a thin cuticle bounds the stem. Within this is a hypodermal portion three cells thick, and within this, again, is a collenchyma-like tissue about as thick. The chlorophyll band, about three cells wide, lies immediately within the last-mentioned tissue and occupies the central portion of the cortex. A relatively narrow inner cortical portion separates the chlorophyll band from the cambium. This inner part consists of a discontinuous hard-bast ring and thin-walled parenchyma. The former abuts on the chlorenchyma. The wood and the pith present no characteristics of interest in the present connection. In addition to the chlorophyll band, chlorophyll occurs also in most of the inner cortical parenchyma, in the medullary rays of the wood, and in the outer pith-cells.

The chlorophyll band is a relatively narrow tissue which lies rather deeply in young stems, but in older ones much nearer the surface (see table of measurements below). The cells are either cuboid or slightly elongated. If the latter the long axis is tangential to the surface.

With increase in diameter certain changes take place in the stem which are most marked in the cortex. Cork is formed in very small stems. In a stem 2 mm. in diameter and 5 cm. from the tip it was observed in the hypodermal cells, where a considerable amount of periderm was organized. This is more pronounced in branches 4 mm. and still more in those 7.5 mm. in diameter. The phelloderm, however, is not formed until the stem is somewhat older. In a stem 1.2 cm. in diameter the phelloderm was about two cells in thickness and was chlorophyll-bearing; in a branch 1.7 cm. in diameter the amount of chlorophyll-bearing phelloderm was so great as to considerably increase the width of the chlorophyll tissues. The chlorophyll early leaves the wood and the pith; in a stem only 7.5 mm. in diameter it was confined to the outer portion of the cortex.

The following measurements were made:

Diameter of branch.	Distance from tip.	Width of cortex.	Width of chlorophyll band.	Depth of chlorophyll band.
mm.	*cm.*	μ	μ	μ
1.5	2	208	38.4	70
2	5	256	32	80
4	20	448.2	25.6	64
7.5	35	1162	64	64
12	65	1494	80	19.2
17	95	1147	73.6	41.6

COVILLEA TRIDENTATA. (Plate I, B, and fig. 5.)

The plant from which the branch studied was taken is growing near the road a few meters east of the Laboratory building. Sections were cut at the following distances from the tip: 5, 10, 20, 35, 65, 95 cm., and were 1, 1.5, 3, 4.5, 7.5, 9.5 mm., respectively, in diameter.

The young and angular stem, 1 mm. in diameter, has the following general relations of its tissues: Within the epidermis, which has a rather thin cuticle, lies the broad chlorophyll band, which is about three cells in thickness. A discontinuous hard-bast ring is placed immediately within the chlorophyll band. This is made up of larger and of smaller groups, of which the former lies opposite the angles of the stem. More or less stony tissue also is found in the same ring. Between the groups of mechanical tissue is thin-walled parenchyma. Within the hard-bast ring, and separating it from the cambium, are the distal ends of the medullary rays and parenchyma between them. There is nothing noteworthy in the present connection regarding either pith or wood.

The chlorophyll band is made up of cuboid and elongated cells, of which the latter have the long axis placed parallel to the surface of the stem. In addition to the outer chlorophyll band, chlorophyll is found sparingly in the medullary rays both of the cortex and of the wood and in the pith also.

With increase in diameter the stem exhibits certain changes in its general structure, of which the most important in the present connection are to be found in the cortex. Cork is organized early and is superficial. The phelloderm is in direct contact with the chlorophyll band and probably contributes chlorophyll-bearing cells to the latter, although this was not definitely determined. The other changes in the cortex do not affect the distribution of the chlorophyll and may be neglected.

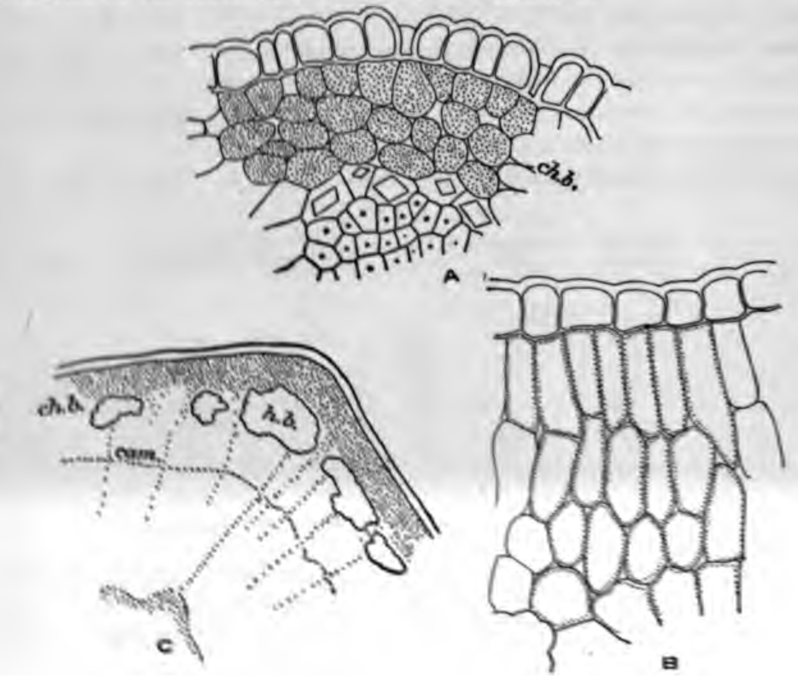


FIG. 5.—*Covillea tridentata*: *A*, transverse section of stem 5 mm. in diameter, showing character of spongy tissue of chlorophyll band; *B*, transverse section of leaf, showing palisade character of subepidermal chlorenchyma; *C*, cross-section of stem 1 mm. in diameter, to show general distribution of chlorophyll. Lettered as in fig. 3.

The order of disappearance of chlorophyll from the stem was not followed. In a stem 1.5 mm. in diameter chlorophyll was observed in the pith, in the medullary rays of wood and of cortex, and in the chlorophyll band. In a stem 5 mm. in diameter, however, it had practically disappeared from all tissues deeper in the stem than the chlorophyll band; in a stem 9.5 mm. in diameter no traces of chlorophyll were to be detected outside of this band. No chlorophyll was found in another branch 2 cm. in diameter and 145 cm. from the tip, although the primitive chlorophyll band, but without chlorophyll, was still present.

The following measurements were made:

Diameter of branch.	Distance from tip.	Width of cortex.	Width of chlorophyll band.	Depth of chlorophyll band.
mm.	*cm.*	μ	μ	μ
1	5	176	48	16
1.5	10	256	118	19.2
3	20	332	64	48
4.5	35	421	80	80
7.5	65	421.6	64	32
9.5	95	664	64	80

EPHEDRA ANTISYPHILITICA. (Fig. 6.)

Ephedra occurs in the wash at the foot of Tumamoc Hill, to the west of the Laboratory. The specimen selected for observation forms a dense shrub about 2 m. high, which has found refuge from predatory cattle by growing under a large *Acacia greggii*. As is well known, the plant has an appearance much like that of scouring rush, which is due to the numerous slender branches that are divided into sections of about 50 cm. each. These branches are the only green ones on the plant; the older ones are covered with a rough bark, which is of gray color.

The general structure of one of the green branches may be outlined as follows: An epidermis with heavy cuticle and with deeply sunken stomata bound the stem. The stomata are regularly disposed in a manner depending on the arrangement of certain mechanical tissues within the cortex. I refer to bundles of fibers which occur at intervals of about 50 μ on the inner edge and abutting on the epidermis. Between the bundles the surface of the stem is somewhat depressed and in these channels the stomata are placed. The cortex is composed mainly of palisade cells which are chlorophyllaceous, but fibers in groups are scattered in an irregular fashion through the cortex. The wood and the pith in young stems do not contain chlorophyll; in older stems, however, the medullary rays of the wood are supplied with chlorophyll.

The younger portions of the green branches, with a diameter of 1 mm., have chlorophyll in the cortex only and, as mentioned above, this is palisade. The cells range in length from 15 μ to 65 μ, and of these the shorter are uniformly near the woody cylinder. In stems 1.5 mm. in diameter the inner cells have lost their palisade character and are more or less cuboid. This is probably owing to the growth in diameter of the stem and to the consequent tangential stretching and radial compression of the cortex. Finally, these inner cells become elongated in a direction parallel to the surface, so that their primitive character is wholly lost.

In stems 2 mm. in diameter the diameter of the woody cylinder and the thickness of the cortex are noticeably increased as a result of the activity of the cambium. The topography of the chlorophyll apparatus is likewise

somewhat changed, since it has been extended to include the medullary rays of both wood and cortex. The organization of the phelloderm, which may be observed in stems 4 mm. in diameter, also modifies the chlorophyll distribution. The phellogen extends from the outer part of the subepidermal palisade layer to about the layer of cells which is next to the inner chlorophyll-bearing cells. In the outer cells the outer ends are converted

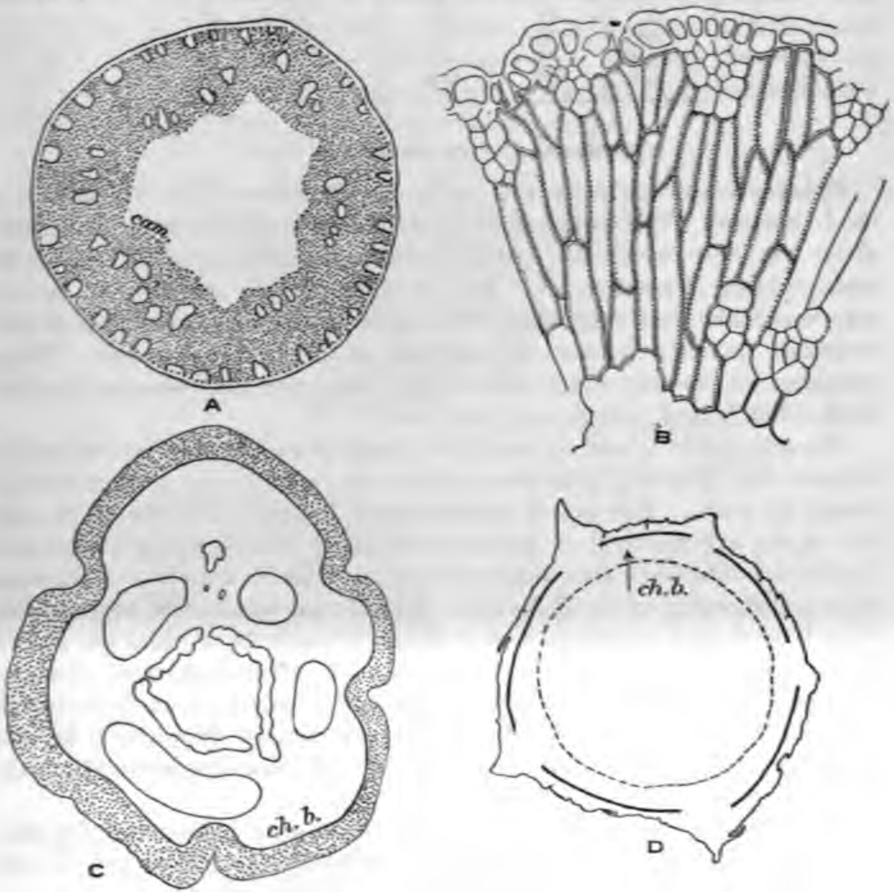


FIG. 6.—*Ephedra antisyphilitica: A*, cross-section of green branch, a detail of which is shown in *B*. *B*, portion of stem to show structure of chlorophyll band of cortex. *Fouquieria splendens: C*, transverse section of stem 5 mm. in diameter; bases of stout spines which entirely encircle stem are not shown. *D*, section of older stem in which the chlorophyll band has become discontinuous as a result of the stem's growth (see text). *ch. b.*, cortical chlorophyll band; *cam.*, cambium.

by transverse walls into phellogen; in the inner cells, however, which have the long axis parallel to the surface in stems of this size, the division walls forming the phellogen are parallel to the long diameter of the cells. The bark thus originating is lens-shaped. It therefore happens that a cross-section of a stem 4 mm. in diameter shows a portion of the primitive cortex with chlorophyll-bearing cells and a portion of it converted into cork which

is, of course, without chlorophyll. However, at this time, in addition to segments of the original chlorophyll band, there extends beneath the cork at least one layer of cells which are chlorophyllaceous. It does not appear that the phelloderm contributes to the chlorophyll apparatus. From these circumstances it happens that stems which appear brown or gray in color and give no visible indication of chlorophyll are, however, chlorophyllaceous.

With the further development of the bark the primary cortex, except the single layer of cells which contain chlorophyll and which lie immediately within the phellogen, is entirely cut off, and with this process the most considerable portion of the chlorenchyma of the stem disappears. When chlorophyll quite left the stem was not learned. In a stem 7.5 mm. in diameter, in which no trace of the primary cortex remained, chlorophyll was to be seen in the outer medullary rays of the woody cylinder, in the rays of the cortex, and sparingly in parenchyma connecting the ends of the latter. Stems 1.1 and 1.5 cm. in diameter give no trace of chlorophyll in either wood or pith.

FOUQUIERIA SPLENDENS. (Fig. 6.)

Fouquieria occurs on dry, well-drained slopes. The plant used in this study is growing on Tumamoc Hill not far below the Laboratory.

The young stem, 5 mm. in diameter, is characterized by three well-defined areas, namely, (1) an external shell of sclerenchyma, within which is (2) parenchyma containing chlorophyll, and within this is (3) the inner cortex, wood, and pith. The relative extent of the three divisions will be apparent from the sketches. The external shell is part of the primary cortex and is morphologically the base of the spines of the stem, which in turn are morphologically midribs of the primary leaves. The cells of the external shell early take on the characteristic thickening and turn brown, and in stems 5 mm. in diameter the shell forms a continuous covering. When the stem increases in diameter, however, the mass of sclerenchyma connected with each spine draws away from the mass connected with every other spine, and the intervening space is occupied by a waxy tissue which is somewhat greenish. The area covered by these two classes of tissue is more and more disproportionate in amount as the stem grows until in the oldest parts the surface is practically all covered by the newer tissue.

The chlorophyll is confined to the parenchyma, which lies immediately within the shell of sclerenchyma or the newer tissue that succeeds it. It is composed wholly of cuboid, thin-walled cells with prominent intercellular spaces.

So far as I have observed, chlorophyll is always present in the stems of *Fouquieria*, of whatever size. In stems 5 mm. in diameter the chlorophyll band forms a continuous ring in the outer portion of the cortex. As the shell base of each spine becomes separated from the base of the other contiguous spines in the manner above described, breaks occur in the chloro-

phyll band opposite the center of each sclerenchyma mass, due perhaps to the fact that the covering of the chlorophyll band at that point is heavy and opaque, so that the chlorophyll in the older stems occurs opposite the newer external tissue only (fig. 6, D). This circumstance, together with the translucent condition of the newer portion of the external covering, is largely responsible for the green coloring of the older parts of the plant.

The following measurements were taken:

Diameter of stem.	Width of exterior covering.	Depth of chlorophyll in the stem.
mm.	μ	μ
5	498	818
8	500	832
30	1162	894

FRANSERIA DUMOSA. (Plate 3, B, and fig 7.)

Franseria is a globoid shrub about 50 cm. high which is growing in some abundance on the north slopes of Tumamoc Hill and on the aerial mountain-deltas in the western portion of the Laboratory reservation. It is characterized by numerous slender branches of approximately equal length, which spring either from the short main stem or from the bases of the older branches. It thus happens that new branches may replace dead ones and maintain the usual form of the plant when the latter fall away. The triangulate leaves are sage-colored, and for the most part are borne near the tips of the branches, although there is great variation in this regard, depending apparently on the adequacy of the water-supply. In times of extreme drought only small leaves remain on the very tips of the branches.

The external tissues of the branch vary with its age and presumably with the conditions under which growth took place. The most recent portions are green and dark purple in color. The surface has a shining or waxy appearance, due to secretions from hairs, certain of which are provided with chlorophyll (fig. 7, C). Below the younger portions the branch is roughened by narrow longitudinal furrows and ridges, the latter of which are continuations of the epidermis. This condition marks the first appearance of bark. Towards the base of the stem the furrows widen, the ridges disappear, and the entire surface becomes black and of a shaggy character. As will be shown below, chlorophyll occurs in the cortex up to the last condition of the bark given. With scarcely an exception chlorophyll is found in the cortex within 2 to 5 cm. of the bases of the secondary branches, from which it follows that a very large percentage of the entire carbon assimilative area of this plant, as *Fouquieria* and others, must be in its branches.

The general structural characteristics of the branches, particularly of the cortex, are indicated by the accompanying sketches and may be outlined

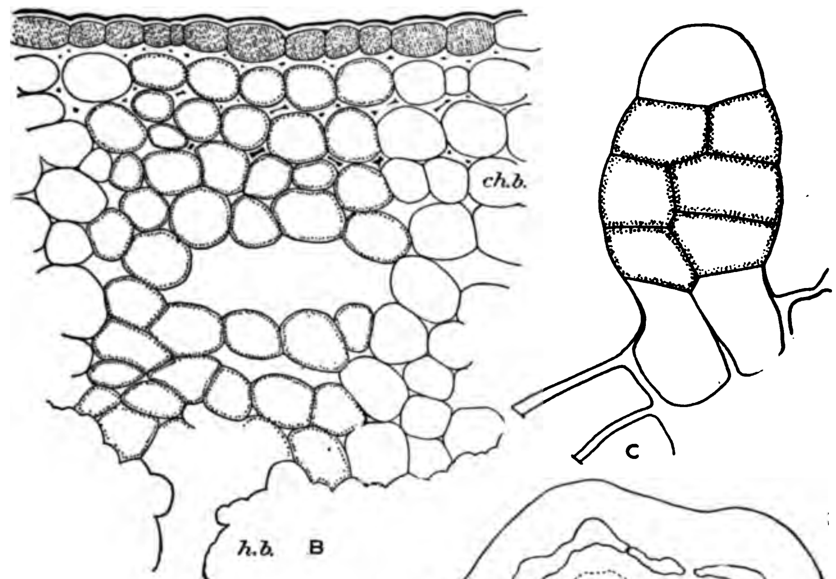
A

B

A.— KŒBERLINIA SPINOSA. Branch from a plant which is situated on the old Ft. Yuma Road along the bottom land of the Santa Cruz River. Nov. 8, 1906.

B.— FRANSERIA DUMOSA. An entire plant taken from the northern slope of the Tumamoc Hill. April 25, 1907. Franseria is an evergreen.

as follows: The epidermis has a relatively thin cuticle. At a distance of 1.5 cm. from the tip its contents are colorless, but in the older parts a dark purple pigment is present. As previously mentioned, multicellular hairs and other hairs occur; these are to be found most abundant, perhaps, where no pigment is present in the epidermis. The secretion from these hairs, which is soluble in chloroform and ether, is so copious as to nearly submerge them, and covers the stem as far as the location of cork. The cortex



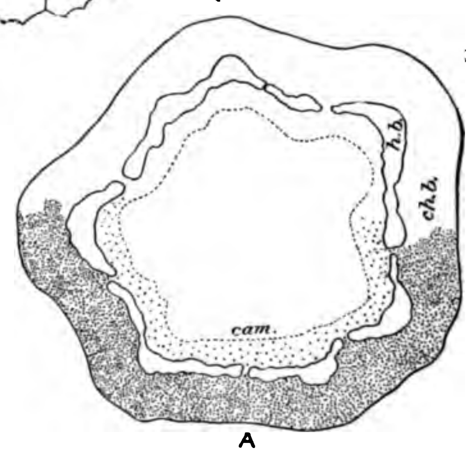


FIG. 7.—*Franseria dumosa: A*, transverse section of stem 1.23 mm. in diameter, showing general distribution of chlorophyll; *B*, detail of *A*, to show character of cortical chlorenchyma; *C*, secreting hair from young part of stem, to show presence of chlorophyll, which is indicated by stippling, on periphery of cells. The cells of the epidermis do not contain chlorophyll.

in stems 1.23 mm. in diameter and 5 cm. from the tip is composed of four well-defined tissues, which, enumerated from without, are collenchyma, parenchyma, hard bast, and soft bast. The collenchymatous and the parenchymatous portions are chlorophyll-bearing; some chlorophyll may also be found in the ground-tissue between the hard bast and the cambium. The parenchyma exterior to the hard bast contains chlorophyll and is made up of cuboid cells with large intercellular spaces.

Except in the very youngest branches, *i. e.*, those less than 1.13 mm. in diameter, no chlorophyll occurs either in pith or wood, but in a section of this diameter it was observed in both. It occurred in the outer cells of the pith and in the primary medullary rays of the wood, as well as in parenchyma between the ducts.

The formation of cork and the activity of the cambium make important modifications in the chlorophyll apparatus as above described. The cork cuts off all tissue exterior to the ring of hard bast. There does not appear to be a definite cork-cambium, but the cortical cells are directly converted into cork. About the time cork is formed the parenchymatous cells within the hard-bast ring become much enlarged, the chlorophyll content is greatly increased, and these cells replace in function the primary chlorophyll band, which has become cork. Through the activity of the cambium more deeply placed chlorenchyma and hard-bast rings are formed, which eventually replace the secondary chlorenchyma much as the latter has replaced the primary chlorenchyma. The exfoliating process appears to be repeated several times, until in the oldest portions of the branch the portions cut off and those reformed no longer contain chlorophyll. In this repeated formation, destruction, and reformation of chlorenchyma *Franseria* is peculiar among the plants observed.

The following measurements were made:

Diameter of branch.	Distance of section from tip.	Depth of outer chlorophyll band.	Width of cortex.
mm.	*cm.*	*μ*	*μ*
1.13	1.5	21	......
1.23	5	26	294
1.67	11	126	525
2.46	15	231	588

KŒBERLINIA SPINOSA. (Plate 3, A, and fig. 8.)

Kœberlinia, leafless except in seedling stage, occurs as isolated plants mainly in the bottom-lands of the river. It avoids for the most part the dry slopes of the mountains and the mesa. The plant studied is growing near the southeast corner of the cemetery at Tucson. It is about 1.5 m. high and extends horizontally, so that the diameter of the shrub may perhaps be 3 m. The shrub has in consequence a squat appearance.

In structure *Kœberlinia* shows several striking characters. A cross-section of a branch 3.5 mm. in diameter and 5 cm. from the tip has in the cortex four well-marked regions. It is bounded by an epidermis with a very heavy cuticle, from 80 to 96 *μ* thick, which is pierced by stomal canals. Immediately beneath the epidermis and reaching to it is a band of chlorophyll nearly 0.2 mm. in breadth. This band is bounded on its inner surface by

a ring of mechanical tissue composed of hard bast connected by grit-cells, and within this ring is the thin-walled parenchyma, which separates the hard-bast ring from the cambium. Medullary rays reach to the ring of mechanical tissue. The wood and the pith exhibit no features of interest in this study.

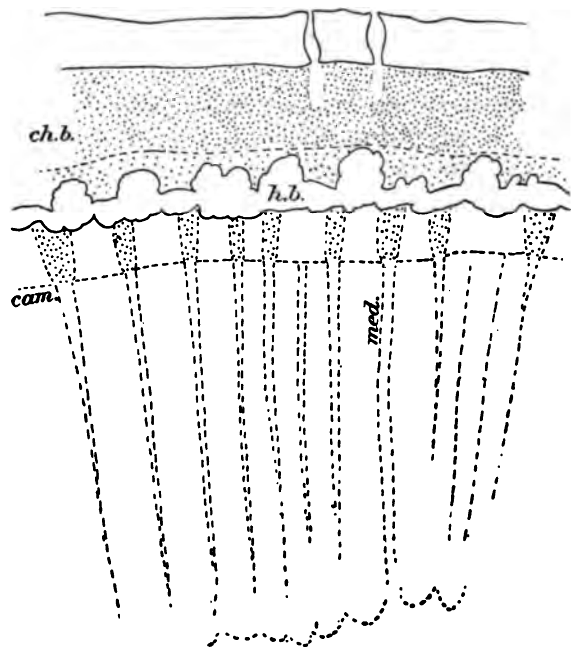


FIG. 8.—*Kœberlinia spinosa:* Segment from cross-section of stem 1.5 mm. in diameter, to show distribution of chlorophyll.

The chlorophyll is practically wholly limited to the cortex. If it is found in the wood at all it is in the outermost medullary rays. The most important chlorophyll-bearing tissue is the subepidermal band which occupies the area between the epidermis and the hard-bast ring. The outer cells are palisade in form; the inmost three layers are spongy chlorenchyma or they may be elongated in a tangential direction. The parenchyma, which occurs opposite the grit-cells, and therefore between the hard-bast groups, although forming a part of the chlorophyll band, are morphologically the outer ends of the cortical medullary rays. The cells referred to are exterior to the grit-cells and have become detached from the medullary rays by the assumption of heavy walls by that part of them which lies between the hard-bast groups.

With increased diameter certain changes in the relations of the chloropyll-bearing tissues of the stem take place. The heavy cuticle becomes ruptured at frequent intervals and the spaces thus formed are covered by a many-layered periderm. The cork-cambium arises in the epidermis. As more

and more of the surface of the stem becomes covered with cork the breadth of the chlorophyll band decreases until in the older portions it likely quite disappears. During these processes very little phelloderm is organized, and exactly how the formation of cork cuts off the chlorophyll band was not determined. It is probable, however, that the secondary phellogen strikes deeply into the cortex and cuts out segments of the band. As a result of this kind of cork formation the bark has a characteristic scaly or shaggy appearance.

Chlorophyll disappears from the stem rather early. In a branch 1.5 cm. in diameter it was barely demonstrable in the inner cortex, although the cortex was only 0.75 mm. in thickness.

The following measurements were made:

Diameter of branch.	Distance from tip.	Width of cortex.	Width of chlorophyll band.	Depth of chlorophyll band.	Thickness of cuticle.
mm.	*cm.*	μ	μ	μ	μ
3.5	5	381.8	144	80	80
4.5	20	415	112	88.4	88.4
4.5	35	464.8	192	96	96
8	45	747	112	64	64
15	60	747	192	80	80

KRAMERIA CANESCENS. (Plate 1, A, and fig. 9.)

Krameria occurs on the mesa and low hills as scattered individuals; rarely are there several of them growing together in groups. The plant selected for study is growing on the aerial mountain delta and below to the west of the Laboratory. The shrub attains a height of about 50 cm.; the branches spring from the base, which may be either the primitive stem or the bases of older branches which have died. The newer growth is covered with hairs and beneath the hairy covering by its green color the stem shows that it contains chlorophyll. During dry seasons the branches are bare of foliage, but in favoring times they are fairly well provided with small, narrow leaves.

Branches of a plant about 50 cm. high were studied, and as usual sections were taken from several at measured intervals from the tip. In cross-section a branch 1.5 mm. in diameter and 5 cm. from the tip presents five well-defined regions, namely, the epidermis with its rather thin cuticle, a broad subepidermal chlorophyll band, the inner portion of the cortex with its groups of hard bast and occasional crystal-bearing cells, and the wood and the pith. Regarding the wood and the pith there is nothing noteworthy from the present point of view.

Chlorophyll is to be found from the epidermis to the pith in practically all of the parenchyma. It occurs sparingly in the epidermis in stems 2.5 mm. in diameter, although it was not seen in one 1.5 mm. in diameter. *Parkinsonia* also has chlorophyll in the epidermis of the young branch; this is an unusual condition in the desert perennials. The most important

chlorophyll-bearing tissue is the subepidermal band which extends to the interrupted ring of hard bast. Chlorophyll is also to be found in the medullary rays and in the outer cells of the pith.

The chlorophyll band is composed of a single layer of much-elongated palisade cells, or of a single layer of palisade cells and one tier of nearly cuboid cells which lie within, *i. e.*, towards, the woody cylinder.

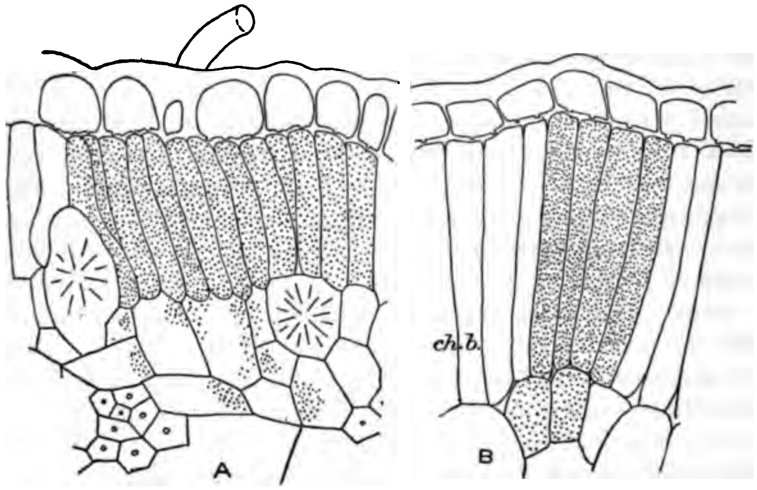


FIG. 9.—*Krameria canescens: A*, transverse section of leaf, showing character of the subepidermal palisade cells; *B*, cross-section of stem, to show structure of cortical chlorophyll band; same magnification as in *A; ch. b.*, cortical chlorophyll band; *h. b.*, hard bast; *med.*, medullary rays.

With increase in diameter, up to 2.5 mm. and 30 cm. from the tip, there is no marked change in the appearance of the chlorophyll apparatus of the stem, but in a branch 3.5 mm. in diameter and 40 cm. from the tip a marked modification is found. This is largely owing to the formation of cork. The phellogen arises in the parenchyma *between the hard bast and the cambium* and by its activities cuts the entire chlorophyll band off from the living portions of the stem. As an immediate consequence the chlorophyll band becomes at once a portion of the cork. In a branch 2.5 mm. in diameter no chlorophyll was found in the wood or pith and none also in the most inner portion of the cortex. It was confined to a layer of cells, or to two layers, immediately beneath the phelloderm.

The following measurements were made:

Diameter of branch.	Distance from tip.	Width of cortex.	Width of chlorophyll band.	Depth of chlorophyll band.
mm.	*cm.*	μ	μ	μ
1.5	5	240	67.2	25.6
2	20	232.4	83.2	28.8
2.5	30	249	60.8	32
3.5	40	415	......	......

OLNEYA TESOTA.

Olneya is a small tree of which but a single specimen is growing near the Laboratory domain. There is a grove of this species at Robles Pass, Tucson Mountains, and another east of Pima Canyon, Santa Catalina Mountains. These habitats are rocky lower mountain slopes; it does not occur in this vicinity on the bottom-lands of the river or on the mesa.

Branches 1.5 mm., 4 mm., 5.5 mm., 9 mm., 1.15 cm., 1.35 cm., and 2 cm. in diameter were studied; the sections were cut the following distances from the tip: 1, 20, 35, 50, 65, 90, and 120 cm.

A stem 1.5 mm. in diameter is characterized by an epidermis not well defined, by a chlorophyll band that is frequently interrupted by masses of collenchyma, and by a relatively narrow inner cortical portion. The wood has a large proportion of wood parenchyma. The medullary rays extend to the chlorophyll band of the cortex through the gaps in the hard-bast ring.

In addition to there being chlorophyll in the so-called chlorophyll band of the cortex, it is to be found in branches 1.5 mm. in diameter in the medullary rays of the cortex, but not in the wood or the pith. In branches 4 mm. in diameter and 20 cm. from the tip, however, chlorophyll was seen in the medullary rays of the wood and in the wood parenchyma.

A characteristic change in the distribution of the chlorophyll in the stem and in its relations to various tissues takes place with increase in diameter. As the circumference becomes greater the groups of hard bast are pulled farther and farther apart, the spaces between are filled with parenchyma, and as this tissue is really the distal ends of the medullary rays, the latter in older stems become fan-shaped. This condition recalls that observed in *Celtis* and in *Prosopis*. The chlorenchyma is increased in amount by the activity of the cork-cambium also. Periderm is to be seen in stems 9 mm. in diameter. It is formed by the subepidermal phellogen, which also gives rise to phelloderm that contains chlorophyll. In the older stems the chlorophyll band is about one-half periderm and one-half primary cortex.

The chlorophyll early disappears from the woody cylinder. In a branch 9 mm. in diameter it could be found in neither pith nor wood, and in branches 2 cm. in diameter it was confined to the outer portion of the cortex and did not appear to be functional.

The following measurements were taken:

Distance from tip.	Diameter of branch.	Width of cortex.	Width of chlorophyll band.	Depth of chlorophyll band.
cm.	*mm.*	μ	μ	μ
1	1.5	160	48	38.4
20	4	415	80	32
35	5.5	498	54.4	48
50	9	780	118.4	70.4
65	1.15	1079	160	64
90	1.35	1162	160	64
120	20	1660	160	96

PARKINSONIA ACULEATA, P. MICROPHYLLA, AND P. TORREYANA.

(Plate 4 and figs. 10 and 11.)

Parkinsonias are small trees which occur in this vicinity in habitats that usually are distinct. *P. aculeata* is found native on the lower slopes of the Coyote Mountains, about 50 miles west of Tucson, but is cultivated in the gardens of the city. *P. microphylla* occurs on Tumamoc Hill and on the low, dry hills in the western portion of the Laboratory domain. *P. torreyana* is growing in the wash at the western base of Tumamoc Hill. The three species are green in all parts, from which the common name, *palo verde*, is derived. *P. aculeata* and *torreyana* carry more leaf-surface, or at least larger leaves, than *microphylla*, in which they are extremely small. In each species portions or all of the leaves fall away during unfavorable seasons. The general structural relations of the stem do not need special notice; they will be apparent from the discussion of the chlorophyll apparatus.

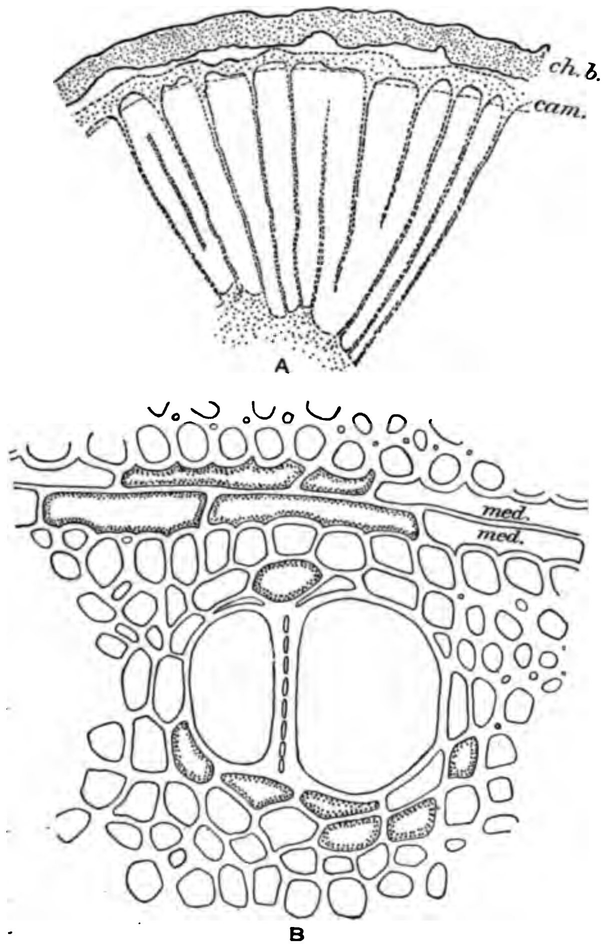


FIG. 10.—*Parkinsonia microphylla: A*, segment of stem 3 mm. in diameter; *B*, transverse section of woody cylinder to show presence of chlorophyll in wood parenchyma adjoining a duct and in the medullary rays. As in all the other sketches the stippling indicates the presence of chlorophyll.

Young branches, *i. e.*, those 1 cm. or less in diameter, are abundantly supplied with chlorophyll, which is distributed in characteristic fashion from epidermis to pith. In general terms this distribution may be defined as follows: It occurs in the cortex as three separate bands concentrically placed in the medullary rays of cortex and of wood, in certain of the wood parenchyma, and in the pith. This is the maximum chlorophyll

older stems, owing to changes in structure incident to pment by which the various chlorophyll-bearing tissues ed or ose their chlorophyll contents, this distribution is greatly

pidermis is usually or at least frequently well supplied with chloro- s applies to stems 1 cm. or less in diameter, although a branch *rreyana* was examined which was 2.25 cm. in diameter and which, less, still had chlorophyll in the epidermis. It may be remarked in that this branch showed another characteristic which is unusual in *sonia*—the woody cylinder did not contain chlorophyll. As will lat the ordinary se- of disappearance of from the stem, the epi- followed by the pith od.

most prominent mass of yll-bearing tissue in the and the one that gives the racteristic of the tree, is cortical chlorophyll band. s chlorophyll tissue is the . It has been iden- s 8 cm. in diameter, sent in the oldest parts, me or perhaps most instances within a few centimeters of se of the tree. It varies in width from 83 μ to 246 μ and its outer surface lies from 83 μ to 500 μ beneath the surface of the stem. In structure the chlorophyll band is wholly of spongy tissue. The cells are cuboid and thin-walled.

FIG. 11.—*Parkinsonia torreyana:* Segment of stem 7 mm. in diameter, to show the distribution of chlorophyll. Lettered as in preceding figures.

Within the outermost band of chlorenchyma is a ring of mechanical tissue composed of alternating groups of hard bast and of heavy-walled parenchyma (which later become grit-cells?). A second band of chlorenchyma lies immediately within this mechanical stratum, which for convenience will be termed the median band of chlorenchyma. In the younger stems the median band is practically continuous, but in the older ones it becomes broken up into distinct masses. From the median band there passes inward, like the spokes of a wheel, the medullary rays of the inner part of the cortex. These rays in the younger branches are well supplied with chlorophyll.

Turning now to the woody cylinder, we find that the medullary rays, a portion of the wood parenchyma, and the pith are chlorophyll-bearing. In branches 1 cm. in diameter the entire medullary ray from cortex to the pith is so well provided with chlorophyll that the cut end of the branch under a hand-lens appears grass green. In much larger stems, however, and in smaller ones from a less healthy plant no chlorophyll, or scarcely any, is to

PARKINSONIA MICROPHYLLA. The species from which this branch was taken deciduous; the branches are green and function as leaves. April 25, 1907.

be found in the wood. The wood parenchyma in the immediate vicinity of the ducts may contain chlorophyll (fig. 10).

As to chlorophyll in the pith, it need only be said that it occurs sparingly in stems 1 cm. in diameter and is not present in the older and larger branches.

The chlorophyll disappears from the stem in a very regular sequence. It leaves the epidermis first, then the pith, then the inner medullary rays; after this the wood parenchyma, then the medullary rays of the cortex and the median band, and finally, when cork is formed, the outer band. That is, with two exceptions, the chlorophyll disappears from the stem in a centrifugal direction. The exceptions were most marked in stem of *P. torreyana* 8 mm. in diameter, in which practically all of the chlorophyll of the pith, as well as of the medullary rays of the wood, had been removed, but the deeply-placed wood parenchyma near the ducts still contained chlorophyll in considerable quantity.

The leading departures from the chlorophyll conditions shared in common by the three species of *Parkinsonia* are as follows: *P. aculeata:* Branches 7 and 12 mm. in diameter had no chlorophyll in pith or in the inner part of the wood. *P. microphylla:* A variation due possibly to differences in water relations was observed in branches 1 cm. in diameter. One branch, taken from a tree which was apparently poorly supplied with water, had very little chlorophyll in the wood and none in the pith, while another branch of the same diameter, taken from a tree that had been irrigated at frequent intervals, had the maximum distribution of chlorophyll. *P. torreyana:* As may be implied from a previous statement, this species appears not usually to have so much chlorophyll in its branches as the other ones, but an exception was noted in a stem 2.25 cm. in diameter, in which the chlorophyll was in the epidermis and extended into the stem for a distance of 6 mm. This tree was growing in a particularly favorable location in the wash at the west base of Tumamoc Hill.

The following measurements were made:

Species.	Diameter of branch.	Outer cortical band.		Penetration of chlorophyll.
		Depth.	Width.	
	mm.	μ	μ	*mm.*
P. aculeata	7	......	960	0.6
P. microphylla	3	83	83	1.5
Do	10	......	......	0.5
Do	11.5	144	130	1.8
Do	15	112	144	1.5
Do	32.5	160	234	1.6
Do	49	130	246	2
Do	80	160	160	......
P. torreyana	8	64	144	......
Do	10	96	176	5
Do	12.5	96	160	......
Do	22.5	96	196	6
Do	30	128	224	0.4

PROSOPIS VELUTINA. (Figs. 12, 13, and 14.)

Prosopis velutina is the most characteristic tree of the river-bottoms, where in places it forms extensive forests. It varies in size from a small shrub to a well-formed and shapely tree 15 m. or more high. The difference in size depends mainly on the lack or the abundance of the water-supply. Leaves are formed in the spring and are shed in the autumn with a regularity characteristic of deciduous trees of more humid regions.

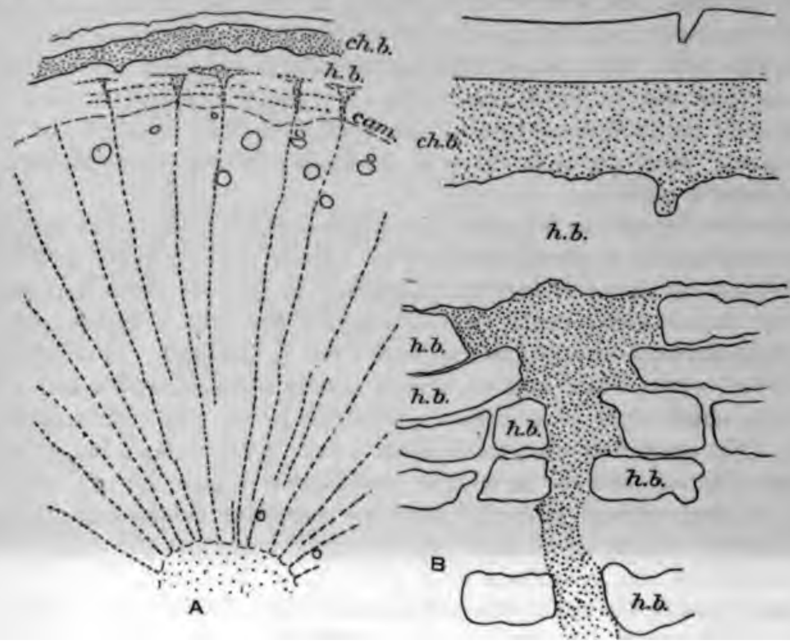


FIG. 12.—*Prosopis velutina:* *A*, transverse section of stem 4 mm. in diameter, to show distribution of chlorophyll; *B*, segment from cortex of stem 7 mm. in diameter, to show relation of hard bast (*h. b.*) to chlorophyll.

The sections of branches studied were cut at nine separate intervals from 3 cm. to 1.23 m. from the tips, and were from 1.3 mm. to 1.5 cm. in diameter.

In several particulars the distribution of chlorophyll in *Prosopis* recalls that in *Parkinsonia*. In the young stem chlorophyll may be found in practically all of the ground-tissue both of cortex and of wood. With increase in size the chlorophyll distribution of the stem becomes greatly restricted and the topography of the chlorophyll apparatus becomes much changed. The general structural relations of the stem will be apparent from the succeeding account of the distribution of the chlorophyll and will not require especial discussion.

The epidermal cells of *Prosopis* do not contain chlorophyll—in this as well as certain other particulars *Prosopis* is unlike *Parkinsonia*. *Prosopis*

stems older than one year have in the cortex a varying number of concentrically placed hard-bast rings which are broken at intervals where the medullary rays penetrate the cortex. Between the rings of hard bast is to be found a thin-walled parenchyma. It is the disposal of the hard bast, together with the disposal of this parenchyma, that in stems 4 cm. in diameter and less determines the character of the distribution of chlorophyll in the inner portion of the cortex. A cross-section of a stem 4 mm. in diameter shows the chlorophyll-bearing cells of the cortex arranged in the general form of a net, in which what may be called the warp is the medullary rays and the woof the parenchyma, or that portion of the parenchyma that separates the rings of hard bast. The woof of the texture in young stems occurs along the inner side of the secondary hard-bast rings, but in oider stems, for reasons given below, it occupies practically the entire space between the bast groups.

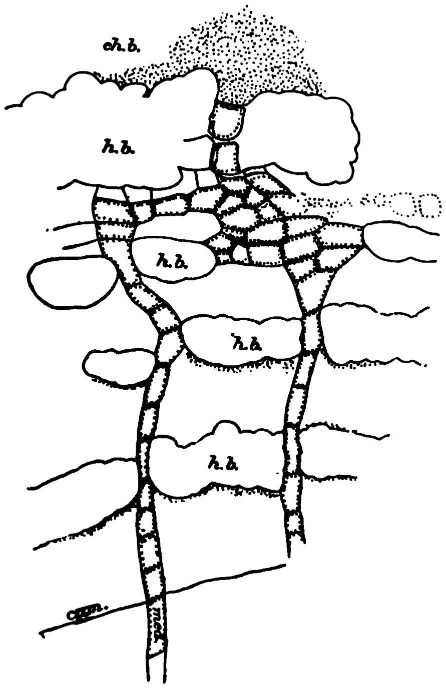


FIG. 12.—*Prosopis velutina:* Detail from inner portion of cortex of stem, to show structure of distal ends of medullary rays and connection between outer mass of chlorophyll (*ch. b.*) and the more deeply lying chlorenchyma. *h. b.*, hard bast; *ch. b.*, cortical chlorophyll band.

With increase in size of the stem certain changes occur in the chlorophyll apparatus which are dependent on the dispositon of the other cortical tissues. As the circumference of the stem becomes greater the groups of bast become farther apart, while at the same time, as a result of the radial pressures set up, the rings are approximated nearer and nearer to each other. The most notice able effects of these changes occur naturally in the more peripheral portions of the cortex. The primary medullary rays in young stems extend to the hard-bast ring, and when by the growth of the stem this is broken up and its members are connected by stony tissue the rays extend to the *stony tissue* of this ring. Secondary hard-bast rings are formed within the primary one, between the segments of which pass the medullary rays. With the growth of the stem the outer groups of secondary bast separate from one another, just as happened with the primary bast groups, and the more peripheral rings become closely pressed together. These general relations not easily described will be apparent from the sketches.

In the young stem the medullary rays of the cortex are about one cell wide, but as the hard-bast groups separate from each other with the growth of the stem the rays broaden to fill out the resulting gaps until the ends are many cells wide. The most striking effect is associated with the primary rays. They feel the effects of the growth sooner than the other rays and of a consequence the ends of the primary medullary rays are fan-shaped and present in cross-section a very striking appearance. From this manner of differentiation and development of tissues the amount of chlorenchyma in the young cortex is much increased.

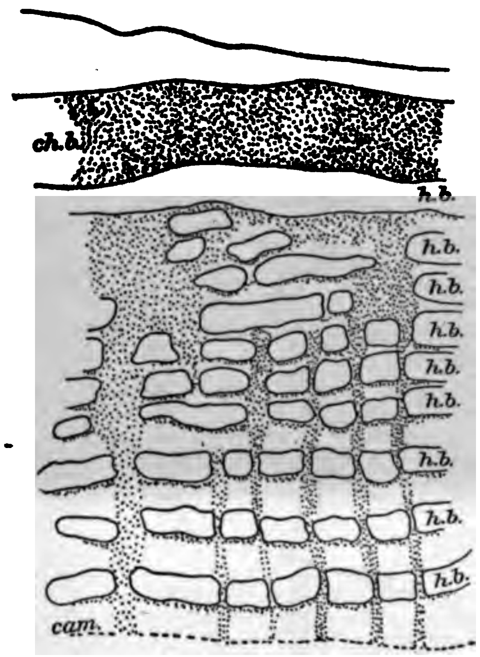


FIG. 14.—*Prosopis velutina:* Segment of stem 1.5 cm. in diameter, in which is shown arrangement of rings of hard bast and their relation in the chlorophyll apparatus.

Growth of the stem works also to modify the relations of the outer chlorophyll band in a way that may be noted. In a branch 1.3 mm. in diameter an unbroken ring of hard bast separates the chlorophyll band from the inner cortical tissues. In a branch 4.5 mm. in diameter the hard-bast ring becomes broken up into groups, as was described above. The connecting cells at first with thin walls become, finally, stony tissue and contain chlorophyll. As a result the outer band is joined to the medullary rays and practically the entire chlorophyll apparatus is welded into a single tissue. Later, however, the outer band of chlorophyll becomes again separated from the inner chlorenchyma by the further development of the same stony tissue.

As in *Parkinsonia*, chlorophyll occurs in the medullary rays of the wood, in the parenchyma of the wood, and in the pith. In order of disappearance it leaves the pith and the inner medullary rays first; it lingers behind in the parenchyma surrounding the ducts. The exact time, however, that the chlorophyll leaves the woody cylinder was not learned. In a branch 4 cm. in diameter no chlorophyll was to be seen in the wood, and it did not extend deeper than 0.5 mm. beneath the surface of the stem.

The later history of the chlorophyll apparatus is connected with the formation of bark. This is one of the factors which brings about the changes in appearance of the stem which are characteristic of it at different times during development.

In the early part of the first year of growth the branch is smooth and of a dark purple color; later in the season it becomes green and is flecked with minute purple or red dots and is somewhat rough to the touch. During the following season and for an undetermined period afterwards it remains green. Finally this is replaced by a gray surface which also is slightly rough and which persists for several years. Branches 8 cm. in diameter may have this appearance. The gray exterior is in turn replaced in old stems by a rough bark black in color.

The color of the youngest stem is due to red and blue pigment in the epidermis, and the texture of the surface to the unbroken cuticle. As the stem becomes older, phellogen arises in the epidermis, which forms primary periderm and primary phelloderm. Ruptures appear in the cuticle, which become pronounced and allow the chlorophyll to be seen through the corky tissue. As the stem becomes larger the amount of cork increases, the amount of phelloderm especially becomes greater, and at length entirely conceals the underlying chlorophyll. This condition lasts a long time and constitutes the third stage, as presented above. Finally, in still older stems a secondary phellogen is organized deeper in the cortex than the chlorophyll band and separates this tissue to its ruin from the remainder of the stem. After the formation of the secondary phellogen the stem does not as a consequence contain more chlorophyll.

The following measurements were taken:

Diameter of branch.	Distance from tip.	Depth of chlorophyll	Width of chlorophyll band.	Depth of chlorophyll band.
mm.	*cm.*	*mm.*	μ	μ
1.3	3	0.65	32	32
1.6	18	0.80	32	48
2.25	33	1.25	64	64
3.3	48	1.65	64	48
4.5	63	2.25	64	48
5	78	2.32	64	48
7	93	3.30	64	48
9	108	3.30	106	32
15	123	......	100	48

SALIX NIGRA.

Salix occurs in some abundance along the banks of the bed of the Santa Cruz River. Some of the trees may attain a height of 15 m. or more.

A section of a branch 3.5 mm. in diameter 30 cm. from the tip shows the following general relations of the tissues: Beginning with the periphery there is (1) a protective portion about four cells deep, which does not contain coloring matter, and a protective portion beneath this about two cells in thickness that is pigmented; (2) a parenchymatous tissue which is chlorophyllaceous; (3) groups of hard bast and inner ground-tissue and cambium; and (4) finally, the woody cylinder.

The chlorophyll occurs in the parenchyma, which is immediately within the many-celled protective layer but not in a well-defined band, in the medullary rays of cortex and of wood, and in the pith. As is usually the case with growth of the stem, the distribution of the chlorophyll is changed and it becomes much reduced in amount. In a branch 8.5 mm. in diameter and 90 cm. from the tip the chlorophyll was confined to the outer portions of the medullary rays and to the cortex; and in a branch 1.3 cm. in diameter and 150 cm. from the tip it had left the woody cylinder entirely and was to be found only in the subepidermal chlorophyll band. The fate of the chlorophyll band was not learned.

SAMBUCUS MEXICANA.

Sambucus occurs as scattered individuals by roadsides on the river-bottoms. It forms a small tree from 5 to 8 m. high, with a main stem 15 to 20 cm. in diameter. The tree which was selected for study is growing by the Hospital Road east of the Laboratory domain. It is about 6 m. high and has a polled appearance, as if most of the shoots were second growth.

The topography of the chlorophyll apparatus presents no unusual characters. In the youngest portions of the branch, 2.5 mm. in diameter and 0.5 cm. from the tip, all of the ground-tissue is chlorophyll-bearing. That is to say, chlorophyll is to be found from the epidermis to the center of the extensive pith and in all tissues except those already differentiated. There appears to be no distinct cortical band. The chlorenchyma is made up of spongy tissue, which for the most part has very thin walls and prominent intercellular spaces. No change in the distribution of the chlorophyll is to be noted until the stem is about 4.5 mm. in diameter, when none may be found in the pith and but little in the inner portion of the cortex outside of the medullary rays. It occurs in the medullary rays of the wood.

When chlorophyll wholly left the stem was not determined. In a branch 8 mm. in diameter and 25 cm. from the tip, chlorophyll was found in the parenchyma of the primary cortex immediately within the mechanical tissue and nowhere else. In another branch 1.6 cm. in diameter and at a point 1.23 m. from the tip the distribution was found to be quite the same.

The youngest portions of the stem are frequently green, *i. e.*, there is no protective covering for the chlorophyll. The second node is often purple from a red-blue pigment in the subepidermal cells. In the next older node there may in addition be a heavy covering of trichomes. Also, the cork-cambium is laid down early in the development of the branch and takes its origin in the subepidermal cells, so that it happens that some sort of protection against excessive illumination or excessive transpiration, either the leafy covering of the stem, pigmented cells, a hairy coating of the epidermis, or cork is given the chlorenchyma during its entire existence.

ZIZYPHUS PARRYI. (Plate 5 and fig. 15.)

Zizyphus occurs sparingly on the river-bottoms or elsewhere where the water conditions are fairly good. It is a grayish-colored (due to hairy covering) spiny shrub from 1.5 to 3 m. high and bears during favorable seasons a considerable leaf-surface. As is the case with the most of the desert perennials, the leaves fall away with the advent of dry conditions and leave the shrub bristling with spines in a condition very much like the ordinary condition of *Kœberlinia emoryi*.

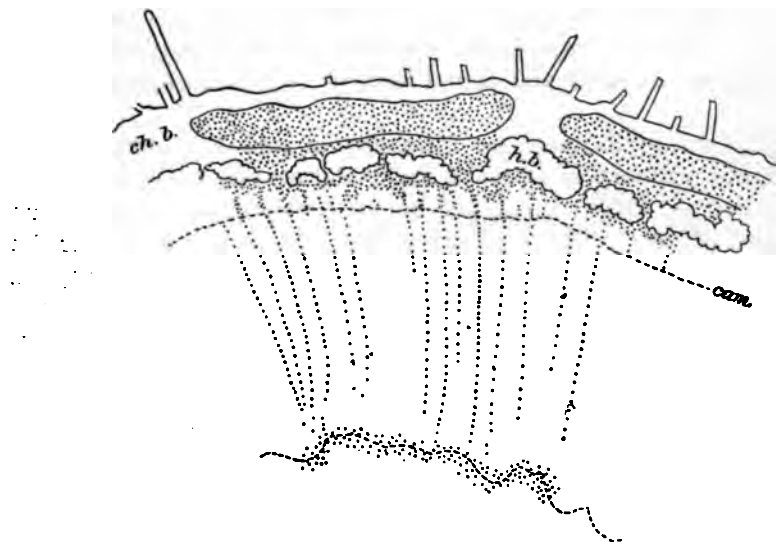


FIG. 15.—*Zizyphus parryi:* Section of stem 3 mm. in diameter, to show distribution of chlorophyll. *ch. b.*, cortical chlorophyll band; *h. b.*, hard bast; *cam.*, cambium.

The young stem of *Zizyphus* shows the customary divisions into cortex, wood, and pith, of which the latter is especially abundant. The main divisions of the cortex are the epidermis with its rather heavy cuticle, a chlorophyll band beneath the epidermis, a hard-bast ring which is discontinuous, and the ground tissue between it and the cambium.

The distribution of the chlorophyll is very much as in other plants. The outer cortical parenchyma, most of the inner cortical parenchyma, the medullary rays, and the outer pith-cells contain chlorophyll. The outer chlorophyll band, which is interrupted at frequent and fairly regular intervals by masses of collenchyma, has a palisade structure, at least in the outer part, of short cells very like the cells in the leaf. The inner chlorenchyma cells are cuboid. The parenchyma and the collenchyma between the chlorophyll band and the groups of hard bast deeper in the cortex contain chlorophyll. The medullary rays of the cortex are also chlorophyll-bearing. The rays either end in the groups of hard bast or pass outward

between them and join the broad band of chlorophyll. Chlorophyll-bearing tissue on the inner face of the ring of hard bast connects the medullary rays. So that there are three rings of chlorenchyma in the cortex, namely, the chlorophyll band and two inner rings separated by hard bast. The medullary rays of the wood and of the pith in a stem 3 mm. in diameter contain small amounts of chlorophyll.

With increased diameter certain changes in the distribution of the chlorophyll occur which should be noted. As usual, these modifications are most marked in the cortex. With lateral stretching, which accompanies the growth of the stem, the groups of hard bast become farther and farther apart and the intervening spaces become filled with a chlorophyll-bearing tissue, so that the relative and actual amount of chlorenchyma is much increased.

In stems 1.4 cm. in diameter the formation of cork has begun. The phellogen appears to take its origin in the epidermis and shows little indication of activity. Only a small amount of periderm was observed and almost no phelloderm. The periderm in the larger branches is colored a deep red and is broken through at intervals by lenticels. No chlorophyll is to be found in wood or pith, although in a stem 1.55 cm. in diameter and 1.6 m. from the tip the cortical chlorophyll band was still to be seen. When it disappeared from the stem, if ever, was not learned.

The following measurements were made:

Diameter of branch.	Distance from tip.	Width of cortex.	Width of chlorophyll band.	Depth of chlorophyll band.
mm.	*cm.*	μ	μ	μ
3	5	192	57.6	19.2
3.5	20	256	76.8	19.2
4.5	35	262.4	89.6	19.2
6	50	381.8	80	22.4
8	80	398.4	73.6	22.4
14	110	664	64	41.6
14.5	140	664	64	32
15.5	160	747	41.6	35.2

ZIZYPHUS PARRYI. Branch from a plant which is situated by the St. Mary's Road near the laboratory domain. Zizyphus is a plant with the deciduous habit. April 25, 1907.

GENERAL DISCUSSION AND RESULTS.

MORPHOLOGY OF THE CHLOROPHYLL-BEARING TISSUES.

Although different in details, the general arrangement of the chlorophyll apparatus in the stems of desert perennials has in many respects a close similarity, for which reason the type arrangement can be presented by describing an ideal stem.

The ideal branch will have a diameter of 5 mm., with the following structural divisions: (1) an epidermis with a relatively heavy cuticle; (2) a hypodermal tissue about three cells in thickness; (3) an outer cortical chlorophyll band, which is somewhat wider than the hypoderm and which lies immediately beneath it; (4) a hard-bast ring; (5) the inner portion of the cortex, in which are the distal ends of the medullary rays, perhaps secondary hard bast and undifferentiated ground-tissue; (6) the woody cylinder and the pith. Medullary rays are prominent and wood parenchyma is present in considerable amount.

Such being the general structural relations of the stem, the chlorophyll is distributed as follows: The leading chlorophyll-bearing tissue is the subepidermal band, and this is true not only because it is the most extensive of the stem, but also, as will be shown below, because it retains chlorophyll the longest of any of the tissues. Moreover, it is rarely changed into any other kind of tissue, but persists as chlorenchyma until, as a general thing, it is cut off by the formation of cork.

The medullary rays, both of the wood and of the cortex, contain chlorophyll. The distal ends of the medullary rays extend into the cortex and between the groups of hard bast and abut on the inner face of the chlorophyll band, by which circumstance the chlorenchyma of the stem is for the most part bound into one continuous system. In addition to the chlorophyll band and the distal ends of the medullary rays, there is in the cortex another kind of chlorenchyma, namely, the ground-tissue, that lies immediately within the hard-bast groups. In the woody cylinder, in addition to the medullary rays, the wood parenchyma also may contain chlorophyll. This is true especially of those cells that are placed near the ducts. Lastly, the pith may be chlorophyllaceous. Generally speaking, therefore, with the exception of certain embryonic tissues in the cortex, all of the parenchyma of the stem may contain chlorophyll.

As the stem increases in diameter, certain changes in these tissues, as a whole, and in those which are chlorophyll-bearing, are seen to take place, some of which should be noted. These may be outlined as (1) the gradual disappearance of the chlorophyll and (2) as modifications in the topography of the chlorophyll apparatus, as above sketched.

In the usual condition there is a certain order in the recession of chlorophyll in the stem. This is as follows: It disappears first from the pith;

ther n the m dullary rays of the wood, beginning in the inmost portions; then trom the wood parenchyma; after this, from the medullary rays of the cortex; and, lastly, from the chlorophyll band, or, more usually, the band itself is obliterated. In the exceptional event of chlorophyll in the epidermis of the younger stem, as in *Parkinsonia*, this may leave the stem before any other tissue is deprived of its chlorophyll. Generally speaking, however, with the exception of the wood parenchyma, the chlorophyll of the stem disappears in a centrifugal fashion. Possibly the exception is due to some favoring condition, as the proximity of better air-supply, or more water, or the light may be condensed by the water-content, so that a portion of the contiguous parenchyma may have better light relations than that in the medullary rays.

The chlorophyll band remains active until its organic connection with the inner living portions of the cortex is severed by the formation of cork, or until destroyed by pressure occasioned by growth of the stem. In some forms, as *Cereus* and *Parkinsonia*, as a rule, it is never destroyed during the life of the plant, but persists and gives the color characteristic of each.

SPECIAL STRUCTURAL FEATURES.

We may turn now from a review of what may be called the general condition of the stem as regards the distribution of chlorophyll and take note of phases of the distribution and other characters of the chlorophyll-bearing tissues not shared by all of the plants examined.

Attention may first be called to a curious modification of the chlorophyll band which frequently accompanies increase in diameter of the stem. This is associated with the formation of cork. The chlorophyll band, properly so-called, is an integral portion of the primary cortex; in old stems, however, the outer part of the band may be morphologically secondary cortex. This circumstance occurs in the following manner: When cork is formed, it is likely to take its origin in cells exterior to the chlorophyll band and very close to it. By the activity of the phellogen periderm is organized without and phelloderm within in the usual fashion and in the cells constituting the phelloderm chlorophyll may be found. Consequently it happens that in older stems of certain plants, as in *Celtis pallida*, fig. 3, the outer portion of the chlorophyll band, in addition to being of different origin, may be more recently organized than the inner portion. There appears to be a limit to the thickness of the chlorophyll band brought about by this means, however, as the portion of the band which is of secondary origin has never been seen to be more extensive than the primitive part.

Another point which has to do with the structure of the chlorophyll band relates to the similarity in some cases and the dissimilarity in others of the structure of the band in the stems and the structure of the chlorenchyma of the leaves of the same plant. In all plants studied palisade tissue of some sort was found in the leaves, but in part only of the plants was the

chlorophyll band of the stems also palisade—it was frequently spongy tissue.* There is a relation between the structure of the chlorenchyma of the stem and the foliar habit of the plant which holds in all well-marked cases and which comparative studies on the forms and their relatives may show to be valid in cases now not so clear. The relation may be stated thus: In perennials with no leaves, or with rudimentary leaves, the chlorophyll band of the cortex is structurally palisade tissue. On the other hand, perennials with relatively large leaves, or a large leaf-surface, have chlorophyll bands of spongy tissue. The following-named plants either have no leaves at any time of the year (in mature stage) or the leaves are clearly of a rudimentary nature and the chlorenchyma of the cortex is uniformly palisade: *Aster spinosus*, *Baccharis emoryi*, *Ephedra antisyphilitica*, *Kœberlinia spinosa;* although different in certain regards the outer part of the chlorenchyma of *Cereus* may also be said to be palisade. On the other hand, the following plants have a pronounced leaf-surface and the chlorenchyma is spongy tissue: *Condalia spathulaca*, *Covillea tridentata*, *Fouquieria splendens*, *Parkinsonia aculeata*, *P. torreyana*, *Salix nigra*, *Sambucus mexicana*. The leaves of *Krameria canescens* should probably be considered rudimentary, although of fairly large size; during the driest seasons the plant is leafless. The chlorenchyma of the stem is palisade. *Zizyphus parryi* has a large leaf-surface and the leaves are not unlike those of *Fouquieria;* like *Krameria*, the leaves are usually absent during dry times. The chlorophyll band is palisade. *Parkinsonia microphylla*, as the specific name indicates, has very small leaves, so small that their presence is hardly noted, and yet the chlorenchyma of the stem is of spongy tissue. It should be said also that the leaves of *P. microphylla*, as well as those of the most leafy forms, fall away with the advent of dry seasons.

Whatever may be the significance of this variation in structure of chlorenchyma of stems of perennials, there appears to be a fairly uniform relation between it and the character of the tissues exterior to the band. The exceptions to this relation are at least no more striking than the exceptions to the relation of structure and leaf-habit given above. The relations have to do especially with the depth of the chlorophyll band, the presence or the absence of pigment in the exterior tissues, and perhaps also with the presence or absence of trichomes.

As a rule, the depth of the chlorophyll band may vary with the age of the stem; however, in young stems, *e. g.*, those about 1 cm. in diameter, there is much constancy in this regard. *Aster spinosus*, *Baccharis emoryi*, and *Krameria canescens*, all of which must be considered plants with a reduced transpiring surface, have the following depths of the chlorophyll band: 19.2 μ, 16 μ, 18.8 μ, respectively. These forms have palisade chlor-

*The leaves of *Opuntia versicolor*, and perhaps of other opuntias, do not appear to have palisade tissue, although palisade-like tissue is to be found in the permanent parts, namely, the stems. Compare fig. 14, Biological Relations of Certain Cacti, W. A. Cannon, American Naturalist, 1906, **40** : 27.

enchyma in the stem. With its extremely thick cuticle, 80 μ, *Kœberlinia* is a marked exception to this condition. Contrast the depth of the band as given for these species with that of the stems of *Celtis pallida*, *Covillea tridentata*, *Parkinsonia*—representing the leafy class of parennials. The figures are 96 μ, 48 μ, and 83 μ, respectively. All of these forms have spongy chlorenchyma in the stem.

There is also fair consonance between the kind of chlorenchyma and the kind of tissue exterior to it. In *Aster*, *Baccharis*, *Krameria*, *Kœberlinia*, *Cereus*—plants with a reduced leaf-surface or with no leaves—the chlorophyll band extends to the epidermis. Such is the condition to be met, not alone in young, but also in old stems of these plants, which, however, is *not* the final condition in most of them. In the type of plants with larger leaves, or larger leaf-surface, on the other hand, there is frequently when young, and always when old, some sort of tissue, in addition to the epidermis, which serves as a covering to the chlorophyll band. This may be hypodermal tissue, cork in most plants, or in *Olneya* a curious proliferation of the epidermal cells in the young branches by which a many-layered epidermis is organized. It will be recalled that in the former class of perennials the chlorenchyma is palisade and in the latter spongy tissue.

In yet another structural characteristic the two classes of plants are distinguished. With certain exceptions plants with rudimentary leaves or none have no pigment in the epidermis, *i. e.*, the parts exterior to the chlorophyll band are colorless. But in *Celtis*, *Condalia*, *Olneya*, and *Prosopis* all forms possessing a pronounced leaf-surface, either the epidermis or the hypoderm, or again the periderm, is provided with a pigment which is usually of a dark-red color. In these forms the chlorenchyma is of spongy tissue. An exception to this is found in *Parkinsonia*, which has no pigmented tissues exterior to the chlorophyll band.

The coincidences which have been repeatedly observed of spongy chlorenchyma and pigmented exterior tissues lead to the belief that the relation between the two is something more than a chance association. This is strengthened by the further observation that in palisade chlorenchyma no such exterior pigmented cells are usually to be found.

Although no hard and fast rule can be given, it appears that perennials which have a reduced leaf-surface present the following characteristics regarding the chlorophyll band of the stem: Its structure is wholly or at least in part palisade; it usually lies close to the surface, and the tissues exterior to it usually do not contain pigment. While, on the other hand, perennials with a pronounced leaf-surface possess a chlorophyll band of spongy tissue, there is usually some kind of tissue in addition to the epidermis between it and the surface, and the exterior tissue usually contains pigment.

PENETRATION OF THE CHLOROPHYLL.

The greatest depth at which chlorophyll was found beneath the surface of the plants varied from 0.38 mm. in *Kœberlinia spinosa* to 6.6 mm. in *Cereus giganteus*. In ordinary leaves chlorophyll occurs from 0.04 mm. to 0.35 mm. from the surface. As contrasted with the depth of chlorophyll in leaves, that in the stem is, therefore, from about 9 to 165, or 0.5 to 18.8 times more distant. In these desert plants, of a consequence, there are very unusual conditions to which the chlorophyll of the stems may be subjected and under which photosynthesis may be carried on. The most deeply placed chlorophyll probably has the minimum amount of light, or the minimum degree of aeration, or the least amounts both of air and of light. Adequate water-supply as well as suitable temperature, more surely the latter,* are presupposed to exist.

As is well known, chloroplastids of certain plants may exercise their function of carbon assimilation under exceedingly feeble illumination. Pfeffer (Physiology of Plants, Eng. ed., vol. 1, p. 340) states that photosynthesis may occur at an illumination 1/600000 the intensity of sunlight. It is not surprising, in view of this, in a region where light is so intense as in the desert, that we find chlorophyll over 0.5 cm. beneath the surface (in extreme instances probably much deeper than this).

The light tonus probably plays an important rôle, as indicated by the range of the position of chlorophyll in the stem. This condition is well known in plants inhabiting more moist regions. Chloroplasts of many plants become pale and discolored after a few days in darkness. The paling of grass and of low herbaceous plants in weak light which obtains during a long wet season are familiar examples of the dependence of the chloroplastids of such forms on a constant and considerable supply of light. On the other hand, plants belonging to the Cactaceæ and Coniferæ, as well as *Elodea*, *Chara*, etc., are more resistant and may remain green for a month or more in darkness. But the fact that at a depth of 6.6 mm. the chloroplastids of *Cereus* are green in *old* stems is indication not of survival but of their being functional at the moment. It is not known what the maximum light stimulus may be that the chloroplastids of *Cereus* may endure without injury, but Pfeffer states that chloroplastids of *Elodea* can be exposed to light more intense than 60 times concentrated sunlight without injury. If a comparison of the life conditions of *Elodea* with that of the desert forms is permissible, we might expect the chloroplastids of *Cereus* and of other desert types to be exceedingly resistant to light.

The considerable extent of the chlorophyll apparatus in the desert plants emphasizes another condition which is probably not present in leaves, or if so, to a limited extent only, namely, what may be termed the light stress which the protoplast of the desert plant experiences. The outer chloro-

*Compare distribution of chlorophyll in *Parkinsonia*, p. 23.

plastids are subject to an unknown but high degree of insolation; to which the innermost ones are subject to an unknown but exceedingly small degree. Thus there is experienced at the same moment a very wide range in the intensity of the light stimulus. What the effect on the morphology of the chlorenchyma, especially, of this light stress in such a plant as *Cereus*, in which the chlorophyll-bearing tissues endure throughout the life of the plant, perhaps unchanged, may be, has not been inquired into, but probably it is a very important factor to be reckoned with and one that must be taken into account in studies on this general subject.

The relation of the deeply seated chloroplastids in the stem of such plants as *Cereus* or *Parkinsonia* to air is very different from such relation in leaves, where the character of the structure insures abundant aeration. To a relatively long distance from the source of supply of oxygen and carbon dioxide and small intercellular spaces of the typical xerophyte, is added immobility of stems, so that gaseous exchange between the external atmosphere and that inside the plant, as well as between different portions of the plant, is not aided by various bendings and movements characteristic of leaves. This may result in a condition in which unusually small amounts of air reach the deeper tissues, so for this reason photosynthesis is precluded. Indeed, the manner of recession of the chlorophyll from the stem suggests that poor aeration rather than the lack of sufficient light may be an important factor in limiting the depth at which chlorophyll may be functional. It will be recalled that in *Celtis pallida*, as well as in other forms, the wood parenchyma which surrounds or is most closely related to the large ducts retains chlorophyll after it has disappeared from other portions of the woody cylinder as far removed from the surface or even considerably nearer the surface.

Penetration of the chlorophyll.

Species.	Diameter of branch.	Depth of chlorophyll.
	mm.	*mm.*
Celtis pallida	8	4
Cereus giganteus	(?)	6.6
Condalia spathulaca	1.5	0.75
Covillea tridentata	3	1.5
Fouquieria splendens	30	0.9
Kœberlinia spinosa	3.5	0.38
Krameria canescens	2.5	1.25
Olneya tesota	5.5	2.75
Parkinsonia microphylla	11	5.5
torreyana	22.5	6
Prosopis velutina	3.3	1.65
Zizyphus emoryi	8	4

Pfeffer states (loc. cit., p. 329) that enough carbon dioxide may be taken up by the roots, when transpiration is active, to prevent the more deeply seated chloroplastids at the base of the stem from losing the power of assim-

ilating carbon dioxide when exposed to light for long periods in an atmosphere free from this gas. In *Cereus*, however, the main source of the gas is probably through the stomata, although, as in *Celtis* and other plants, the roots may be of importance as organs of aeration as well.

The table on the preceding page presents the greatest observed depths to which chlorophyll penetrates and remains green in the stems of perennials. Considerable care was exercised in selecting material and the estimates in each instance are probably conservative.

IMPORTANCE OF CHLOROPHYLL BAND.

As has been already discussed, the leading chlorophyll-bearing tissue in the stem is the subepidermal chlorenchyma, which in this paper has been designated the chlorophyll band. This also is the most enduring chlorophyll tissue of the stem. It constitutes practically the entire carbon assimilative apparatus in plants with reduced transpiring surface—a very important part of the apparatus in deciduous plants—as it does the entire apparatus, or nearly so, in the leafless forms. In *Baccharis*, *Cereus*, *Fouquieria*, *Kœberlinia*, *Krameria*, *Parkinsonia*, and *Zizyphus* it exists throughout the life of the plant; in markedly leafy plants its importance is less, perhaps, but still that it is of great moment in their economy can not be doubted. It is least important in the evergreen forms, as *Celtis pallida* and *Condalia spathulaca*.

The chlorophyll band has been identified in the following plants at the several distances given from the tip, which are not supposed to represent the maximum distance in any case, but may do so: *Celtis*, 178 cm.; *Condalia*, 95 cm.; *Covillea*, 95 cm.; *Franseria*, 15 cm.; *Olneya*, 120 cm.; *Prosopis*, 123 cm. The relative importance of the band appears more clearly, perhaps, when its volume in several plants is compared. In order to institute the comparison the diameter of stem nearest 1 cm. was taken, and the measurement of the chlorophyll band applied directly to an ideal stem 100 cm. in length and 1 cm. in diameter. In this manner *Celtis*, with a chlorophyll band 0.025 mm. wide, would have a volume of 0.098 cm. in a stem 100 cm. in length; *Kœberlinia*, 0.415; *Parkinsonia microphylla*, 0.477; *Prosopis*, 0.578. The ratios are, approximately, *Celtis*, 1; *Kœberlinia*, 4.1; *Parkinsonia*, 4.7; *Prosopis*, 5.7. Of these plants it will be noted that *Kœberlinia* and *Parkinsonia* rely mainly or wholly on the chlorophyll band for their carbon assimilation all of the year and *Prosopis* a part of the year, while *Celtis*, which is evergreen, but nevertheless has considerable chlorophyll in its stem, depends mainly on the extensive leaf-surface. With *Prosopis* should be classed *Olneya;* and with *Celtis* should be classed *Covillea* and *Condalia*, whose evergreen habit makes the chlorophyll in the stem of e ss importance in the assimilative processes.

Measurements on the chlorophyll band.

Species.	Diameter of branch.	Width of chlorophyll band.	Depth of chlorophyll band.
	mm.	*μ*	*μ*
Aster spinosus	2	......	19.2
Baccharis emoryi	1.5	......	16
Celtis pallida	3.5	25.6	96
Do	10	25.6	108.8
Cereus giganteus	......	......	581
Condalia spathulaca	2	32	80
Do	12	80	19.2
Covillea tridentata	3	64	48
Do	95	64	80
Fouquieria splendens	5	......	498
Do	30	......	1162
Kœberlinia spinosa	3.5	144	80
Do	8	112	64
Krameria canescens	2	83.2	18.8
Do	2.5	60.8	32
Olneya tesota	1.5	48	38.4
Do	11.5	160	64
Parkinsonia microphylla	3	83	83
Do	11.5	130	144
Do	49	246	130
Parkinsonia torreyana	8	144	64
Do	30	224	128
Prosopis velutina	1.6	32	48
Do	9	160	32
Zizyphus parryi	3	57.6	19.2
Do	14	64	41.6

PERSISTENCE OF CHLOROPHYLL IN THE WOODY CYLINDER.

Chlorophyll in the woody cylinder is a striking characteristic of young *Parkinsonia* and *Prosopis* branches especially, and is found in nearly all of the other desert perennials. Compared to the chlorophyll of the cortex, however, it is likely of little profit to the plant, for the reason that it disappears early from the stem. How long it persists was not learned in any case, since the plants studied did not exhibit annual rings, or in any other way give a clue as to the rapidity of growth.

The subjoined table gives the character of the branch at a time when the chlorophyll for the most part had already left the woody cylinder. The measurements were made on the disappearance of chlorophyll.

Species.	Diameter of branch.	Distance from tip.	Remarks.
	mm.	*cm.*	
Celtis pallida	10	144	No chlorophyll in wood or pith.
Covillea tridentata	7.5	65	Do.
Condallia spathulaca	7.5	35	Do.
Kœberlinia spinosa	15	60	Sparingly present in wood and pith
Krameria canescens	3.5	40	No chlorophyll in woody cylinder.
Olneya tesota	2	120	Do.
Parkinsonia microphylla	15	......	Do.
torreyana	22.5	......	Sparingly present in wood and pith

SUMMARY.

The leading results of this study may be summarized as follows:

1. Young stems of desert perennials contain chlorophyll in most of the parenchyma, both of cortex and of woody cylinder. The most important chlorophyll-bearing tissue appears in transverse sections of the stem as a band in the outer part of the cortex.

2. The epidermis of branches of *Parkinsonia* 1 cm. in diameter may contain chlorophyll.

3. Chlorophyll is present in the phelloderm of the following species: *Celtis pallida*, *Condalia spathulaca*, *Olneya tesota*.

4. There is no chlorophyll in the woody cylinder of *Aster spinosus* or *Baccharis emoryi*.

5. The woody cylinder in young stems of *Ephedra antisyphilitica* and of *Olneya tesota* do not contain chlorophyll; in older stems the woody cylinder of both is chlorophyllaceous.

6. The chlorophyll band in the stems of *Cereus*, *Fouquieria*, *Krameria*, *Parkinsonia*, and probably also in *Zizyphus*, persists throughout the life of the member bearing it. In most plants it is ultimately cut off through the formation of cork.

7. As regards foliar habits the plants studied may be classified into two groups, which, however, are not always well marked. In one class leaves are either rudimentary or wanting; in the other, leaves are present at least during the favorable seasons, *i. e.*, when the water-supply is adequate to their needs.

8. The differences in leaf-covering are accompanied by fairly consistent morphological differences, as follows: The plants with reduced leaf-surface, or with no leaves, have palisade chlorenchyma in the cortex; the chlorophyll band, at least in young stems, lies near the surface; the tissues exterior to the band in young and generally in old leaves do not exhibit protective devices. Plants with a more pronounced leaf-surface, on the other hand, have a spongy chlorenchyma in the cortex; it is usually more deeply placed; and the exterior tissue usually has some protective arrangements, as pigmented cells or a hairy covering.

9. The greatest depth at which functional chlorophyll was found ranged from 0.38 mm. in *Kœberlinia spinosa* to 6.6 mm. in *Cereus giganteus*. This is from 0.5 to 165 times deeper than the greatest depth of chlorophyll in ordinary leaves.

10. The depth of penetration is probably limited by the air-supply rather than the supply of light.

11. The chlorophyll band of the stem constitutes practically the sole engine for carbon assimilation in *Aster spinosus*, *Baccharis emoryi*, *Cereus giganteus*, *Kœberlinia spinosa*, *Krameria canescens*, and the most important

chlorophyll tissue during the most of the year in *Parkinsonia* and *Zizyphus parryi*.

12. The volume of the chlorophyll band for a unit stem has a value of 1 in *Celtis*, 4.1 in *Kœberlinia*, 4.7 in *Parkinsonia*, and 5.7 in *Prosopis*. The least volume occurs in evergreen forms; the greatest in plants which depend in part or entirely on it for photosynthesis.

13. The thickest chlorophyll band is in *Parkinsonia*, which is 246 μ in a stem 4.9 cm. in diameter. The thinnest band is in *Celtis*, which is 25 μ in in a stem 1 cm. in diameter.

14. Chlorophyll usually disappears early from the woody portion of the stem, but in *Parkinsonia* it may be found in stems 1 cm. in diameter.

15. When the chlorophyll band is palisade, the character of the palisade is very similar to that of the leaf of the same plant.

16. The following species were studied: *Aster spinosus* Benth., *Baccharis emoryi* Gray, *Celtis pallida* Torr., *Cereus giganteus* Englm., *Condalia spathulaca* Gray, *Covillea tridentata* Vail, *Ephedra antisyphilitica* C. A. Meyer, *Fouquieria splendens* Englm., *Franseria dumosa* Gray, *Krameria canescens* Gray, *Kœberlinia spinosa* Zucc., *Olneya tesota* Gray, *Parkinsonia aculeata* L., *Parkinsonia microphylla* Torr., *Parkinsonia torreyana* Watson, *Prosopis velutina* Wooton, *Salix nigra* Marsh,, *Sambucus mexicana* Presl., *Zizyphus parryi* Torr.

The Induction, Development, and Heritability of Fasciations.

BY

ALICE ADELAIDE KNOX.

OENOTHERA PARVIFLORA. Fasciation of the main axis, with incipient fasciation of the side branches.

THE INDUCTION, DEVELOPMENT, AND HERITABILITY OF FASCIATIONS.

By Alice Adelaide Knox.

The definition of fasciation given by the earlier writers includes plants with axes which, normally round or polygonal, have become flat, and which, wholly or in part, develop through a linear instead of a cone-shaped growing region. Such stems are commonly referred to as banded or ribbon-shaped; they produce abnormal numbers of leaves and flowers; they possess an altered phyllotaxy; and they usually show bifurcations, or splittings, somewhere through their length. The last tendency is so marked that fasciation may be said to include two tendencies—one toward the enlargement and another toward the division of the axes affected.

Ring-fasciations have circular growing regions, and the upper part of the stem is shaped like a funnel with a cavity continually wider toward the top. The funnel commonly breaks on the side, and the stem finally becomes flat; for this reason they, too, come under the head of the banded forms. The various torsions of stems of this character described by Godron (4),* Masters (3), and others, seem to be caused by inequalities of growth resulting from injuries on the concave side. The fact that the curves may be caused by injury is referred to by Nestler (7) for *Sambucus nigra* and *Sonchus palustris*, and will not be especially noted in this paper. Plate I, and plate II, figs. 1 and 3, give an adequate idea of the vertical development of fasciated axes. The material for the research presented was gathered from the œnotheras of Dr. D. T. MacDougal's experimental ground at the New York Botanical Garden and from the plants of a waste field of *O. biennis* in Bedford Park, New York City. Many years ago Knight (1) advocated enrichment of the soil for the culture of cockscombs, and de Vries also has repeatedly emphasized the necessity of plenty of fertilizer. The experimental garden provided the requisite conditions, but although fasciations were more abundant in the rich ground their prolific production on plants that grew wild in the sandy waste land illustrated the force of de Vries's further conclusion (19) that the innate character of the plant is more important than the environmental factors, significant as he deems these to be.

The life-cycle of biennial primroses divides itself into (*a*) the rosette stage, and (*b*) the adult stage, when the flowering stalks develop and fruit. The

*The figures in parenthesis refer to the bibliography, page 18.

study of fasciation is naturally grouped about these two periods. The character of the fasciated rosette, with broad, linear heart, giving rise to stems flattened from the base, has been made familiar by de Vries (11). In the cultures such rosettes reached a breadth of 3 cm., and the stalk from one of them produced a vegetative line which eventually measured 38 cm. (plate I). In other cases the first evidence of fasciation in the rosette is a bifurcation of the growing region, and two tiny buds sometimes appear even between the cotyledons. The two types of rosettes are illustrated by plate II, fig. 4, and by text-fig. 1. The fasciation of the flowering stalks is far more common than that of the rosette and furnishes the bulk of the material for observation, as well as for histological examination. Usually the rosettes have been plants to be kept for other experimental purposes, but the late branches may be cut at will. The flowering stems studied came mostly from two sets of plants—the wild *O. biennis* and the *O. cruciata* in the garden. There were many ring-fasciations in the two groups, though these have been comparatively infrequently reported. The *O. biennis*, besides simple fasciations and ring-fasciations, showed on many stems, associated with the banding, an indentation or groove, as represented in plate II, fig. 2, running up the upper half of the stem. The groove became wider and deeper as the stem flattened. Simple fasciations, ring-fasciations, and groove-fasciations occurred together, both on secondary and tertiary branches of plants of which the main axis had usually been stunted. Two descriptions may be taken as representative:

FIG. 1.—*Raimannia odorata*, bifurcated rosette.

PLANT 1.—The plant had 11 branches, which were all equal in importance, the main tip having been stunted early in its history. There was consequently no main branch, though *A* was the largest secondary branch. The tip of *A* was also stunted, and it had 11 tertiary branches; of these, 7 were fasciated. The fasciations were split into two or more forks. Two of them showed round instead of flat divisions. In six cases below the bifurcations there were grooves. The secondary branch *B* was also fasciated, with a flat tip. The flattening was in every case associated with old capsules, often with holes bored through.

PLANT 2.—The plant had 9 branches. The branch *A* had 6 secondary branches, all of which were fasciated. Two of them showed ring-fasciations, the others were flat, and two exhibited conspicuous grooves. Of the other branches, one showed a ring-fasciation and the others bifurcations and simple fasciations; 5 of them showed grooves so as to be recognizable. All of the main branches were fasciated. The total number of fasciations on the plant was 15.

There were also in the field three or four examples of the type in which the alteration of form dated from the rosette stage. These individuals were always stalwart plants and produced high, strong stems, of which the main axis was fasciated from the base.

In the *O. cruciata* the fasciations were remarkably well formed. Some of them dated in their development from the rosette period, though usually the branches did not begin to flatten until 20 cm. above the base. Many of them suddenly flattened from the time of the appearance on the stem of a hard protuberance, which was usually cylindrical in shape and sometimes 2.5 cm. in length, but often reduced to a small lump on the stem (plate III, figs. 1, 3, 4, 5). Ordinarily the stem fasciated from the point where the protuberance appeared and one or several of the forks were fasciated. If there were no forks the whole stem at once banded. There were also ring-fasciations, and the three forms appeared on the same plant.

The description of a typical individual is as follows:

C. 6. 2.—The plant developed from a rosette which had been kept in a cold-frame from the previous fall (1904), and most of the branches showed by the early disarrangement of the phyllotaxy and by the shape of the stem that the fasciation had started during the rosette period. There were in all 10 branches, of which 1 was normal; 2 at the end of the second summer were small fasciated rosettes; 7 were repeatedly bifurcated, 3 of them eventually into 9 forks. Of these, 3 showed protuberances at the point of the first bifurcation. One stem had a heavy callus at its base, covering an old injury. In these 1905 plants there were no rings, but they appeared in 1906 on stock from the 1905 seed. The largest fasciation on the above plant measured 4.8 cm. by 4 mm. There was frequently a constriction or channel in the stem below, such as appears in the plant in plate II, fig. 1, but not such as to be histologically akin to the grooves in the wild *O. biennis*.

In the cruciate forms of 1905, on one plant 15 out of 16 branches were fasciated; on another, 10 out of 11. For the microscopic study of this material there were to be examined simple flat fasciations, ring-fasciations, groove-fasciations, and the fasciations associated with the protuberances.

In normal structure stems of Onagraceæ are much alike, and it is unnecessary to call attention to small differences. They possess a continuous bundle-ring, which is bicollateral in character. The medullary phloem is arranged in groups just within and following the line of the xylem. The outer phloem is in very small and inconspicuous groups amid a quantity of parenchyma cells. There is a stereome ring, and peripheral to this chlorenchyma several rows of collenchyma and the epidermis. The medullary rays are but 1 cell in width. The pith consists of large parenchyma cells, and there are many bundles of raphides of calcium oxalate there and in the cortex.

There is a kind of latex system which consists of parenchyma cells which contain a brown secretion, most dense near the phloem, but conspicuous in pith, cortex, and epidermis. Sections stained in Delafield's hæmatoxylin resulted in a bright purple in the cells about to crystallize, in brown or a greenish shade in the latex cells, and in a reddish purple

ı in the secretory cells of the parts exposed to injury. asciations when sectioned show the traditional structure of flat d do not vary from the normal except in outline.

ıons of ring-fasciations, as diagrammed in plate IV, series 3, follow the description of Nestler (8) for *Veronica longifolia* in having, s the primary bundle-ring, a second bundle-ring bordering the of the funnel. This ring originates as a group of meristematic cells center of the medullary parenchyma. Gradually successive groups em appear, arranged in a circle, and these differentiate into typical ral bundle-groups. The earliest group consists of several undifed cells, which show their first tracheæ some sections above their earance. The latter groups in their earliest stage consist of 2 by side, a trachea and a nucleated prosenchymatic cell. The a cells in the center of the pith below the first signs of the ring r than the peripheral cells and more crowded together. The of the stem is already changed from the normal below this point, loss of definite arrangement is seen to precede the formation ems. The secondary bundle-groups gradually increase in size the ring; there appears in the center of the pith a h is the beginning of the hollow of the funnel, and re. ion produces an internal epidermis, cortex, and stereome quence the exact reverse of the primary arrangement in the At the apex the two bundle-rings merge into one. When the eaks, the two rings unite at the break and surround simple flat fasciation. As there are leaves and flowers s well as without the funnel, there are leaves and flowers on both sides of the banded stem.

The structure of the groove fasciation of the wild *O. biennis*, shown in plate IV, series 1, presents a case analogous to this. At an early stage of development a portion of the cambium is destroyed, the bundle-ring broken through, and the space is filled with parenchyma. The expansion and increase of the undisturbed cells results in the constriction *g*, which is the external sign of the groove. In the interstice in the ring a meristem develops in the parenchyma, succeeded by other meristems lateral to it. These differentiate into a line of bundle-groups which merge with each other and with the primary ring. During this process the stem flattens, although it is circular when the meristem appears. The flattening is a slow and at first imperceptible process, and the beginning of the alteration must be sought far below the point where it is visible to the naked eye. The distance of the open groove from the tip is 17 to 26 cm.; the stems are flat and broad 12 to 19 cm. from the tip; the meristem begins from 2 to 4 cm. below the opening of the groove. The early stages of the process may be followed by a reference to plate V, figs. 1 to 3. The origin of the meristem

is represented in fig. 1; a later stage in fig. 2 shows the character of the meristematic groups embedded in thick-walled parenchyma, and in fig. 3 the gradual differentiation into phloem and xylem is pictured. Intermediate between the ring and the groove types is found an example illustrated in plate IV, series 4, of what is classed by Nestler (8) in *V. longifolia* as an "imperfect ring." In this the meristems arise in the pith, a ring of bundles develops there, and the ring passes over to one side until it touches the primary bundle-ring, with which it then fuses. At this point the flattening of the stem first becomes marked. In one individual the lysigenous cavity, characteristic of the ring-fasciations, formed within the second bundle-ring and passed out into the cortex when the two bundle-rings merged. Stems with the protuberances on the plants of *O. cruciata* when sectioned (plate IV, series 2) reveal conditions similar to those of the two types preceding. The medullary parenchyma cells in the center of the stem become smaller and more closely crowded together. A meristem then arises in the pith and, after differentiating into a secondary bundle-ring, becomes part of the primary ring, as in the intermediate or ring-groove type. The composite ring then bulges out at the point of fusion, and a portion of it is cut off to form the protuberance. This cylindrical process (plate V, fig. 4) possesses a woody bundle-ring, but there is no apical meristem and, near the tip, primary tracheæ and sieve-tubes run irregularly across its axis (plate V, fig. 6). Above this are irregular, yellowish callus cells (plate V, fig. 5). In a very common variant of its structure, serial sections show, in the pith below the protuberance, a group of cells formed of tracheæ and sieve-tubes, which run transversely and in great confusion. As this group passes toward the periphery and touches the primary bundle-ring the regularity of arrangement is disturbed in the latter, and is only restored after the knob has been entirely cut off from the stem. In another variant the meristem does not appear below the protuberance, nor does the stem fasciate. In a case of this kind the cortex around the main stem was found to be eaten off by insects, the growing region injured, and the lower buds forced out. This is simple abortion of the main axis, with destruction of leaves and buds, which leaves the surface of the aborted stem in the form of a hard and smooth projection. The variations of these regions, of which there may be said to be almost as many as there are specimens, together with the variations of the rings and grooves, are all manifestations of the same principle. The early conditions of one are doubtless similar to the conditions of all, and for this reason special interest attaches itself to the young stages of any of them.

A young protuberance with accompanying fasciation was found in a stem of *O. cruciata*, illustrated in plate III, fig. 6, which was cut in September from one of three slow-growing plants which had elongated 20 cm. from the rosette stage. The phyllotaxy was disturbed for 3 cm., and the leaves

abnormally crowded for 1.5 cm. Transverse sections of a growing region revealed callus over the main tip, just above the pith. The procambial strands about the callus seemed unaffected by the injury to the apical meristem and were continuing their activity. Longitudinal sections of a second plant (plate v, fig. 7) showed callus at the tip of the main is in the former position of the apical cells. Beneath it tracheæ and e-tubes had differentiated and ran irregularly, many in a transverse ction, across the apex. A section of this stem is seen in plate v, fig. 8, shows the callus and the apical conditions. The slight depression er the callus is surrounded by a ring-shaped meristem (plate v, fig. 7). tip has evidently been injured, the meristem has spread in a circular ti and has become distributed as a ring. As enlargement takes ie tip of the stem, its apex will project as a protuberance of greater velopment, showing transverse bundle-elements beneath a mass When unequal growth pushes the callus to one side the ring the stem becomes flattened. The origin of the injury which allus formation is to be found in the surrounding plants. In 20 of *O. cruciata* next these individuals larvæ were feeding, and as es of one of the three in question were freshly eaten, and as another a larva within the stem in the lower part, these insects were ly the agents which attacked the young tips.

e relation of certain insects to the œnotheras is known to be a constant nd more than one genus is recognized as parasitic upon them. The found in Bedford Park and in the experimental grounds are species *ipha*, a tiny grayish moth with spotted wings. The eggs are laid leafy tips and, later, larvæ are abundant in the apices, the capsules, and the pith of stalwart plants. They are particularly common in rosettes toward the latter part of the summer, and as they develop many bind together the leaves to form a shelter and feed among the tender tissues in the winter and again in the very early summer. Most of them eat only young leaves and never reach the meristem; many devour and destroy the apical tissues; while still others irritate or injure them. They are found not only in the rosettes that come from seed, but in those which form in late summer at the ends of old branches to carry over a perennial growth. The fasciated rosettes of late summer frequently appear in pairs, and it is common to find callus and inhibition of growth between the two (plate v, fig. 9). The condition of the branch seems to indicate that the main axis has been destroyed and the side-buds injured as they were forced out. Such branches commonly have circular meristems in the pith, surrounding spots of brown discoloration of the sort which develop about masses of dead cells.

A second kind of injury may arise through the ovipositors of the insects. In the pith of woody stems of *O. cruciata*, *O. parviflora*, and *O. biennis*, and in the capsules of *O. grandiflora* and other forms, are larvæ closely related to those in the rosettes. Those which undergo metamorphosis in the

1.—OENOTHERA HYBRID. Fasciations developed from a bifurcated rosette.
2.—OENOTHERA BIENNIS. Grooved stem with fasciation above.
3.—OENOTHERA CRUCIATA. Ring fasciation.
4.—OENOTHERA BIENNIS. Fasciated rosette.

(See also text figure.)

capsules of *O. grandiflora* are *Mompha brevivitella*, known at one time as *Laverna œnotheræ vorella*, and in May and again in July the insects are constantly invading the tips. The slightest irregularity in the arrangement of the young leaves during or just preceding the flowering period, an appearance like that shown in plate III, fig. 2, or such as might result from some external mechanical interference, indicates that the tip when sectioned will prove to be fasciated or bifurcated. There is no sign externally of the fasciated outline in these tiny tips, merely reddish color, inequality of development, or a tiny aperture suggesting a callus. Microscopical examination proves ring-fasciations and protuberances to be abundant, and simple fasciations occasional. The development at this stage covers less than 5 mm. of the stem, but is none the less perfect. Two such apices are diagrammed in plate V, figs. 10 and 13. In many tips are found long, needle-like incisions, illustrated in plate V, figs. 11, 12, and 13, as if made by an ovipositor. About these the cells have hypertrophied, and cylindrical meristems are forming. Throughout the stems at intervals are small areas surrounded by hypertrophies and meristematic conditions (plate V, fig. 15). These are akin morphologically to the meristems in the pith of the old rosettes, and are like those about the track of the larvæ in stems in which the pith is infested with the latter. All of them are readily recognizable because of the purplish intercellular secretions, seen in plate V, figs. 11, 12, 14, 15, and the changes are those which customarily follow in the neighborhood of dead cells. Tips of this appearance collected July 27, 1906, were bifurcated, if not definitely fasciated; none of them were normal; and there were "stings" of various sorts in them all.

The anatomical structure of rings and grooves and of the protuberances proves them to be variations of a single type, for the essential features of their development are the same. The protuberance varies so greatly in its structure and in its morphology that its simplest form is a mere callus associated with a few irregular bundle-elements projecting from the side of the stem (plate III, fig. 4, and plate V, fig. 10, *k*). It is easy to conceive cases in which the injury is so small as to be impossible of detection. Incisions in young meristems are quickly obliterated by the turgidity and growth of the surrounding cells (plate V, fig. 12), and it may be assumed that many fasciations are caused by injuries too delicate to follow in any but the initial stages. Only chance enables one to find such stages, and innumerable tips may be sectioned without avail. To a stimulus of this nature, obscure in its histological effects, the simple fasciations must owe their origin. They occur on the same plants with those more easily detected, and may themselves, when bifurcated, be recognized while comparatively young. Yet the stimulus is slow to produce the abnormal condition, and the irritating cause is concealed before the effect is seen. In a tip of *O. biennis* which contained an active larva, a group of very small parenchyma cells had differentiated in the pith. This is the condition that

precedes a ring-fasciation, though as yet no ring-fasciation was apparent. In all wild *O. biennis* the stems were infested with larvæ below the fasciations and the grooves full of callus, yet it was impossible to find intermediate conditions. A plant with a fresh larval trail up the side fasciated after a month of elongation from the rosette stage, but by the time the character of the tip was well determined the first effects were obscured by the later growth. Unequal formation of wood on the two sides at the base of fasciated stems may be taken as an indication of local inhibition. Transverse sections of the lower, round part of branches, which are flat above, usually reveal variations in the width of the woody ring. The difference may be s t or, in a few cases, as in plate v, fig. 16, very marked and accom- ned by callus formation. In the groove-fasciations (plate iv, figs. 1*b*, width of the primary wood where it adjoins the groove, at *xx*, is wer than at *yy*. This is also found to be true in sectioning the rosettes n late summer from the old stems (plate v, fig. 9).

t has been said applies to plants out of doors. It seemed probable different state of things would hold in the greenhouse. Yet the ted rosettes in the greenhouse have in the stems circular meristems brownish discolorations and a significant feature of their development -sidedness of growth and a forcing out of the axillary branches. ttes of *O. cruciata* planted June 16, 1906, and kept in the greenhouse g the summer, were subject to such conditions in the pith. These, the rosettes of *O. parviflora* of 1905–1906, showed rough places on the les and midribs of the leaves, incurling of some of the leaves in the growing tip, and ruffling of the margins. The *O. parviflora* planted in the summer of 1905, in December, showed larger and longer leaves on one side than on the other. There was then no sign of linear growth, but in April they began to fasciate, and in May all four plants were fasciated. Frequently the rosettes tip up, owing to the premature development of a lateral branch (plate ii, fig. 4), so that one side is higher than the other. This looks as if there were inhibition of growth on the concave surface. The result of further growth is often a complete torsion of the fasciated main axis with fasciation also in the side branches. In studying fasciation, species with compact symmetrical rosettes are much to be preferred. *O. grandiflora* is among the impracticable forms, for the side branches normally come out very early. A double rosette of *Raimannia odorata*, a near relative of the œnotheras, the plant illustrated in text fig. 1 and in plate v, fig. 17, when sectioned was found to have been injured below the bifurcation, and at this point (*xx*) there was inhibition in the formation of wood. Only the bifurcated fasciations can be detected at the start, and these are of comparatively rare occurrence. It is evident, however, that the rosettes under cover are not exempt from outside injury, and insects may readily enter the greenhouse through the open ventilators, besides the many which habitually live there.

The extensive experiments of de Vries, which have led him to consider certain fasciations hereditary to some extent, made it desirable to test its inheritability in these cultures. Pure seed was saved in 1905 from fasciated plants of *O. cruciata*, and of *O. muricata* from Kansas. The *O. cruciata* came from material originally collected by Mr. S. H. Burnham at Lake George, New York, in 1903. Of his 15 plants, 7 afterward fasciated in the main stem, and 3 of them when grown produced "curious elbow-shaped structures" on the stems. These protuberances were variants of those which appeared in the later cultures. Pure seed from the fasciated individuals was sown in 1904, and 5 plants saved out. These fasciated in the main and side branches, and from them pure seed was sown in February, 1906, and 57 plants saved out. In September, 1906, counting the main stems only, 5 of these were stunted and 2 normal; there were 30 fasciations and bifurcations associated with protuberances, 12 simple bandings, 3 unflattened bifurcations, and 5 ring-fasciations. In the normal stock plants there were in one group of 3 individuals, 1 ring and 2 bandings; in another of 4 plants, 2 protuberances, 1 bifurcation, and 1 simple fasciation; a third, of 4 individuals, contained some fasciated side-branches on each plant. The seed of the *O. "muricata"* was sent by Mr. H. F. Roberts from Manhattan, Kansas, in 1904. The first sowing was made in November, 1904. Although distributed as "*muricata*," it proved to be an elementary species removed from the *muricata* type. Two out of the three plants saved fasciated in the rosette stage and bloomed in the summer of 1905. From one of these pure seed was saved and sown in February, 1906. In September, 1906, out of 43 plants, 26 individuals were fasciated, 3 stunted, 2 bifurcated, and 12 apparently normal. Counting only the flattened tips, 60 per cent were fasciated. In the 3 control plants from unfasciated stock, 2 were fasciated and 1 stunted. The control in each case fasciated as readily as did the fasciation cultures.

Aside from the series which were run as special tests there were numerous examples of fasciation in Dr. MacDougal's general collection. In 1905 fasciation was found in 55 individuals, including *O. lamarckiana*, *O. muricata*, *O. biennis*, *O. oakesiana*, *O. strigosa*, *O. gigas*, *O. nanella*, *O. grandiflora*, *O. lamarckiana* × *O. biennis*, and *O. cruciata*, besides many forms of doubtful identity. In 1906 it appeared in 86 individuals, representing 34 different cultures and a correspondingly wide range of species. Next to *O. cruciata*, *O. parviflora* fasciated most abundantly. The plants were in four different lots from Maine and in one lot from Madrid. All of the individuals fasciated in 50 per cent of their branches. Of the *O. grandiflora* from Alabama, 14 plants were fasciated. In the *O. ammophila* all 5 plants were fasciated in main and side branches. In one group of 4 plants of *O. lamarckiana*, from a parent raised after a succession of pure cultures from seed originally sent from de Vries in 1901, all 4 plants were fasciated in the main stems. The anomaly can scarcely be considered hereditary in

all of these forms, gathered in from all over the world, nor can it be regarded as the sporadic appearance of latent characters. The fact that in many series from normal races, 100 per cent of the individuals planted out fasciated, though no selection was exercised in saving the rosettes from the large numbers of seedlings originally planted, strengthens the inference that its development is due to local causes. One is led to conclude that there have been prevalent in the garden and in this region during the summers of 1905 and 1906 swarms of insects whose attacks upon the growing tips were particularly insidious and stimulative without being at the same time destructive. It happened, too, that several species of the primroses were markedly susceptible to the injuries, and that the conditions of light and nutriment were favorable to vigorous development. Given similar conditions of culture, the factors involved in the production of the fasciations are the specific mode of attack of such insects, the character of the plant, and the rapidity of development; the second of the three is the most important, as it is true that in two adjacent groups of *O. biennis*, one will fasciate and the other will not. It is also true that the form of the fasciation varies with the group affected. Thus *O.* "*muricata*" from Kansas, *O. parviflora*, *O. ammophila*, and *O. grandiflora* developed simple-banded fasciations, while rings and protuberances appeared on the *O. cruciata* and grooves on the wild *O. biennis*. The *O. cruciata* from the Lake George stock differed from the *O. cruciata varia* (?) from Hamburg, which may be what de Vries calls a poor race. Of this *O. cruciata varia* (?) 40 plants sown at the same time with the Maine cultures, of which the rosettes were bifurcated, failed to show fasciation either in the rosettes or branches.

This group of plants flowered much earlier than the others, which calls attention to the importance of the late development of the individual. Most of the fasciations date from the period just preceding the opening of the flowers in July, and they flatten among masses of fruits, or at a point where the stung flowers have fallen off and left the stem bare. From this time the eggs of the momphas are laid, the larvæ develop, and new swarms of imagos begin to emerge toward the end of the summer, at once proceeding to sting new tips. Those apices which have passed the period of greatest vigor gradually dwindle away and die, but leafy axes, leafy rosettes, stems ready to flower through September, all soft tissues in a thriving condition, then fasciate in greater abundance proportionately than earlier in the season, for their limited number makes it more certain that they will be attacked by the recent invasion of the new swarm. In the rosette stage the rate of growth is also important. It is seldom that the insect reaches the apical meristem of a quick-growing plant, for the rapid formation of new leaves supplies sufficient food for the larva, and the formative region remains untouched. Sections of numbers of young rosettes containing larvæ easily prove that the insect ordinarily feeds above the apex or at its side. Though plants are often unaffected by the parasites, doubtless swarms occasionally

OENOTHERA CRUCIATA. 1. Young protuberance. 2. "Stung tip." 3. Old protuberance and bifurcation with one fasciated branch. 4. Protuberances associated with the flattening of the stem. 5. Protuberance surrounded by fasciations. 6. Early stage in the formation of a protuberance.

develop whose mouth-parts are sharper than those of their fellows, or whose habit it is to bore deep for the youngest and most tender food. In the same way there are swarms of imagos which have longer ovipositors, or which show a preference for the center of the apex rather than the axils of the embryonic flowers. If the character of the attacks of the insects varies with the character of the insect swarm, this should account for the widespread appearance of fasciation over one restricted locality, while in adjacent areas, beyond but insignificant barriers, no fasciated plants are found.

The "curious" habit of fasciated stems in that those of annuals are at first round and later flatten, while those of biennials originate large and flat and stay so, has been noted by de Vries (11). In the primroses under observation this seems to be accounted for by the state of development at the time of the sting of the insect. In the cultures of *O. parviflora* rosettes planted in the summer of 1905, and kept over, fasciated during the winter; those sown in February elongated quickly after being placed out and fasciated in the upper parts of the branches. Two plants of the February sowing, which grew more slowly than the others, were fasciated rosettes in September. In general, plants or branches which were in the rosette stage in July and August, or at the time when the insects were laying their eggs and the larvæ were hatching, fasciated as rosettes and produced flat stems the following season. Plants in the flowering state during the same period fasciated in the upper part of the stems. Plants elongating from the rosette stage in September fasciated comparatively low down on the stem as in plate III, fig. 6. Any plant, moreover, may fasciate in its rosette stage the first season, and in the upper part of its side branches the second season. To secure the most striking results in New York, seed should be planted in April or May and allowed to remain out of doors in the rosette stage through the summer. Plants from seed sown in February begin to elongate too early to show linear growth long before the flowering tips are ripe. So many of the wild plants are aborted in the main axis that one may assume that the tip is eaten off by larvæ soon after the plant elongates from the rosette stage. Among the wild plants there were many larvæ in the field in June in the young shoots. The side-branches are doubtless injured as they are forced out, for the callus in the grooves of some of the branches and in the lower parts of the cavity of the rings in others indicates early effects of injury in these secondary branches.

The conditions of culture, as has been already stated, were favorable to the vigorous growth of the garden plants. Individuals were from 2 to 4 feet apart and were well-fertilized and watered. The interesting experiments of de Vries and of Hus (22) at the Missouri Botanical Garden suggest that if some of the unfasciated plants had been subjected to different conditions they too might have fasciated. It is possible, also, that if the plants had been planted in April instead of in February the result might have been different. The environment must, however, be suited to the

individual needs, for seed from the fasciated wild *O. biennis* of 1905, in which the tendency toward fasciation was so marked, when sown in the garden in 1906 produced only one fasciation. The plants of this group flowered very early, however, and the time of sowing may have been as important a factor as the change of environment, or even more so.

That fasciation can be produced by mechanical injury has been known for many years, and Sachs (6) and Goebel (16) both treat of the old experiment where, by cutting off the epicotyl of certain germinating seedlings, the side-branches forced out are flattened. *Phaseolus multiflorus* is most commonly used, while de Vries employed *Agrostemna githago* (19). Nasturtiums also respond readily, and as high as 60 per cent of fasciated individuals was obtained in one water-culture. The injury must occur just after germination, and this has led to the theory that the anomaly is caused by overplus of nutrition rushing to undeveloped centers of growth (16). The effects in the seedling are not lasting, for the flattened branches soon revert to the normal shape. It is possible that the remoteness of the stimulus from the meristems affected may have to do with this. In the œnotheras the injury is to the initial meristem itself, and is of a nature so delicate that no relatively coarse instrument can duplicate it artificially. Repeated attempts were made to induce fasciation in the primroses with incisions by fine sterilized needles, but the needles either destroyed the apex altogether, in which case the side-branch did not fasciate, or failed to reach it at all. Any incisions that could be made were so destructive compared with those of the sort represented in plate v, fig. 13, that the attempt was finally abandoned altogether. It is interesting to note, in support of the theory of the influence of nutrition, that the effects in the œnotheras come during the rosette stage and just before flowering, the times when the elaborated food supply is most abundantly centered at the growing apex.

The discussion of the nature of fasciation has centered about the morphology of the enlarged axis, whether it is the enlargement of a single growing point, as exemplified by Mouquin-Tandon (2), or whether it is the adnation of several axes, as explained by Masters (3). After a careful histological examination of fasciated growing tips of certain Phanerogams and Cryptogams, Nestler (7) found no evidence in favor of congenital adhesion. The growing line gave no sign of complexes of growing points, but represented an enlarged area of meristematic cells. In the œnotheras there has never been any evidence in favor of the concrescence theory. In one single bifurcation for a short distance the epidermis closed around two separate axes, but this was accidental grafting of two separate tips. The phenomena of fasciation are phenomena of multiplication, of increase in numbers of stems and leaves, and of the number of cells which enter into their composition. Once the physiological balance of the growing cells is changed and the chemical equilibrium altered by the peculiar stimulus of the mechanical contact, the tendency to multiply develops, and frequently

continues to the end of the life of the plant. If there were fusion of a definite number of growing regions there would seem to be a definite limit to the increase in the size of the stem and the number of the leaves. Concresence may, and frequently does, occur as a consequence of the bifurcation which is so intimately associated with it, but is an accidental rather than an essential factor, and succeeds rather than precedes the division of the axis. As to the reason for this curious alteration of form in these fasciated stems, one can speak only theoretically. It may be that the banded fasciations arise from lateral injuries in which the inhibition causes the meristem to stretch from the point of attack. This might seem to be illustrated in the case of the rosettes of one-sided development and of the injured stems plate v, figs. 9 and 16. In the ring-fasciations the injury may be to the tip of the growing meristem, and the stresses thereafter distributed in a circular fashion.

Bifurcations are often caused mechanically by the stresses of old and broad fasciations, where the unequal growth and the consequent torsions strain the large growing region into segments through virtue of its unwieldy size. It is to be expected that a fasciation such as that in plate I would soon divide in this way if allowed to grow to maturity. The splitting of the axes may be more frequently mechanical than superficially appears to be the case. We must suppose that in its early stages it is often due to the stresses of vigorous growth in an abnormally large tip. The tensions which are parallel with the vegetative line are greater than those which cross it. A slight disturbance of external conditions, and so of the growth, upsets the equilibrium, and the tension is broken. It must be remembered, as Nestler has shown (7), that the apex is not level, but undulate, and it may be supposed to be constantly changing. Certain delicate adjustments of the stresses may keep the equilibrium until alteration in the rate of growth, due to inequalities in nutrition over so extended an area, upset the balance and free a portion of the axis. In the smaller segments the stresses are not so great; consequently there is increasing tendency toward normal growth, and the smallest bifurcations usually in the end completely reverts to it. Bifurcations sometimes, both in ring-shaped and in flat fasciations, are caused by injury, but in many cases such an origin can not be assigned to them.

Though the development of fasciation has often been referred to external stimuli, there is but one direct reference to its connection with insects. Molliard (15) in 1900 found the larva of a coleoptera within the fasciated stems of *Raphanus raphanistrum* and of *Picris hieracioides*, just below the banded portions of the axis. He suggested that the parasite modified the structure of the vegetative point and changed the mass of the initial meristem from axial symmetry to the symmetry of a line.

Peyritsch (5), in his interesting experiments on the production of abnormalities through inoculation with *Phytopus*, enumerates, among the aberrant

forms found in the Valerianaceæ, "fasciation of side-branches of a slight degree and disarrangement of phyllotaxy." He later says: "All the foregoing anomalies are phenomena of infection and owe their form to the stimulus of a parasite." Although these experiments were never published in detail, and emphasis was laid on phenomena other than those of fasciation, the hypothesis that fasciation was due to infection was evidently in the author's mind. Had he lived longer he might have taken up the subject more specifically and demonstrated it in relation to the Valerianaceæ. He concludes his article with the following sentence: "I am convinced that many instances which have hitherto been explained as spontaneous variations owe their origin to the activity of insects, although a *Phytopus* need not always be the stimulus."

The analogy of the artificial production of fasciation leads one to infer that the insect is but very indirectly the cause, and that the physiology is the physiology of traumatic after-effects. The nature of the changes in the chemical and physical conditions of cells after wounding is as yet but imperfectly understood, and the enormous hyperplasies resulting from the mechanical irritation of foreign substances, especially those associated with the parasitism of insects, are among the most interesting of unexplained physiological phenomena.

The following points are to be emphasized in summing up the foregoing statements:

(1) In the œnotheras the histology of the early stages of development of fasciated stems is varied. Many different forms are found related anatomically to each other and to ring-fasciations. All may occur on the same plant, and the differences between them are morphological, not physiological.

(2) The fasciations arise through the agency of injuries inflicted upon the growing regions by insects. Bifurcations without definite flattening develop through the same set of stimuli.

(3) The injuries must be inflicted upon the initial meristem, and can ordinarily be detected only microscopically, and at the earliest period of the ensuing growth. In such cases their course is almost immediately obscured or obliterated by the development of the surrounding cells.

(4) Injuries may result in the abortion of the whole or part of an axis, or in the formation of small processes on the stem. These malformations are described as "protuberances," and their development is almost invariably associated with fasciation or bifurcation, or both.

(5) Plants infected early in the rosette stage fasciate as rosettes; those infected after the stems have begun to elongate are fasciated only in the upper parts of the branches.

(6) To secure the greatest number of fasciations, the plants should be given the best conditions for their individual development, and the seed should be planted so that the period of greatest vigor may correspond with the time when they are most sure of infection.

(7) The morphology of the fasciated stem is the enlargement of a single growing point. There is no evidence of fusion in the growing region.

(8) When tested in pure cultures, the progeny of fasciated individuals show no greater tendency to fasciation than the progeny of normal plants. The effects of the stimuli causing these malformations in the evening-primrose are therefore to be taken as in no wise heritable.

In conclusion, the writer wishes to express her appreciation of the assistance and of the many courtesies extended to her by Dr. D. T. MacDougal, Dr. H. M. Richards, and by the director and the members of the staff of the New York Botanical Garden. The work was begun under the auspices of the garden and continued under those of the Carnegie Institution of Washington.

LITERATURE CITED.

1. KNIGHT. On the cultivation of the cockscomb. Trans. Hort. Soc. of London, **4**: 321, 1820.
2. MOUQUIN-TANDON, A. Éléments de tératologie végétale. Paris, 1841.
3. MASTERS, M. T. Vegetable teratology. London, 1869.
4. GODRON. Mélanges tératologiques. Mém. de la Soc. nat. des sc. nat. de Cherbourg, **16**: 1871–72.
5. PEYRITSCH, J. Über künstliche Erzeugung von gefüllten Blüthen und anderen Bildungsabweichungen. Sitzber. d. k. Akad. d. Wiss. in Wien, math.-naturw., Cl., **97**: 597, 1888.
6. SACHS, J. Gesammelte Abhandlungen über Pflanzen-Physiologie, **1**: 597, 1892.
7. NESTLER, A. Untersuchungen über Fasciationen. Oesterr. bot. Zeitschr., **44**: 343, 1894.
8. NESTLER, A. Über ring fasciation. Sitzber. d. k. Akad. d. wiss. Wien, math.-naturw. Cl., **103**: 153, 1894.
9. DE VRIES, H. Over de Erfelijkheid der Fasciatiën. Bot. Jaarboek Dodonaea, **6**: 72, 1894.
10. RAMALEY, F. On the stem anatomy of certain Onagraceæ. Minn. Bot. Studies, **1**: 674, 1896.
11. DE VRIES, H. Sur la culture des fasciations des espèces annuelles et biannuelles. Rev. gén. de bot., **11**: 136, 1899.
12. DE VRIES, H. Sur la culture des monstruosités. Comptes Rendus, Paris, **128**: 125, 1899.
13. DE VRIES, H. Über die Abhängigkeit der Fasciation vom Alter bei zweijähriger Pflanzen. Bot. Centralblatt, **77**: 289, 1899
14. LAMARLIÈRE, G. DE. Sur la production expérimentale des tiges et d'inflorescences fasciées. Comptes Rendus, Paris, **128**: 1601, 1899.
15. MOLLIARD, M. Cas de virescence et de fasciation d'origine parisitaire. Rev. gén. de bot., **12**: 323, 1900.
16. GOEBEL, K. Organography of plants. Part I. Oxford, 1900.
17. RENAUDET, G. Contribution à l'étude de la tératologie végétale de la fasciation herbacée et ligneuse. Thèse, Poitiers, 1901.
18. CONARD, H. S. Fasciation in the sweet potato. Univ. of Penn., Bot. Lab. Contrib., **2**: 205, 1901.
19. DE VRIES, H. Die Mutations-Theorie. Leipzig, 1901.
20. DE VRIES, H. Species and varieties. Chicago, 1905.
21. BLODGETT, F. H. Fasciation in field peas. Plant World, **8**: 170, 1905.
22. HUS, H. Fasciation in *Oxalis crenata* and experimental production of fasciation. Rept. Missouri Bot. Gard., **17**: 147, 1906.
23. PUGLISI, M. Contributo alla teratologia vegetale. 1. Fasciazione di *Vescaria reticula*, di *Bunias orientalis*. Ann. di botanica, **4**: 367, 1906.

Description of Plate IV.

Semi-diagrammatic transverse sections of stems; size reduced to two-sevenths of given magnifications.

SERIES 1. *O. biennis.* Successive stages in the development of a groove-fasciation Medullary parenchyma, *mp*; region of cambium, *c*; region of outer phloem and stereome ring, ph_1; region of the inner phloem, ph_2; xylem, *xy*; cortex, *cx*; epidermis, *ep*. × 44.

a. Initial appearance of meristem, *pp*.
b. Appearance of supplementary meristems, m_1, m_2; position of groove, *g*; thick-walled parenchyma surrounding meristems, *pp*.
c. Differentiation of secondary bundles, b_1, b_2, b_3, etc.; callus, *cl*.
d. Gradual enlargement and increase of secondary bundles; region of outer phloem and of stereome ring, ph_3; region of inner phloem, ph_4; xylem, xy_2; cambium, c_2.
e. Union of secondary bundles with primary ring.
f. Last stage before complete fusion with primary ring.

SERIES 2. *O. cruciata.* Development of a fasciation associated with a cylindrical protuberance. Lettering as before. × 18.

a. Initial appearance of meristem, *m*.
b. Differentiation of secondary bundle-ring, b_2, in the pith.
c. Connection of secondary bundle-ring with the primary ring.
d. Fusion of the same.
e. Beginning of formation of protuberance at *k*.
f. Protuberance cut off, *k*.

SERIES 3. *O. biennis.* Development of ring-fasciation. × 25.

a. Appearance of a single meristem, *m*.
b. Development of supplementary meristems, m_1, m_2, m_3, etc.
c. Differentiation of meristems into ring of secondary bundle-groups, b_1, b_2, b_3, etc.
d. Appearance of lysigenous cavity, *ca*.
e. Gradual fusion of secondary bundle-groups. Inner epidermis, ep_2; inner cortex, cx_2; outer phloem of secondary ring, ph_3; inner phloem of secondary ring, ph_4; xylem, xy_2; pith, *pt*.
f. Break in side of ring, making a flat fasciation.

SERIES 4. *O. biennis.* Four stages of the development of a specimen intermediate between Series 1 and 3. 4*a* corresponds with 3*c*. The secondary bundle-ring arises in the middle and passes to the side, where it fuses with the primary ring. × 20.

DESCRIPTION OF PLATE V.

[Drawn with an Abbé camera lucida and reduced to one-third of given magnifications.]

FIGS 1, 2, 3. Transverse sections of stems of *O. biennis*. Successive stages in the early development of a groove-fasciation. Meristem, *m*; thick-walled parenchyma, *pp*; medullary parenchyma, *mp*; cambium, *c*; outer phloem of primary bundle ring, ph_1; inner phloem of same ring, ph_2. Fig. 1 shows the lowest section of the meristem (plate IV, fig. 1*a*). The dark shading in the meristem indicates intercellular secretions. At *x* the cambium has been destroyed. × 430.

FIG. 2. Drawing of meristems in plate IV, fig. 1*b*. Two meristems (m_1, m_2) appear in the break in the ring. × 430.

FIG. 3. Drawing of two groups of secondary bundles, showing first differentiation of vessels. Secondary bundle-groups, b_1, b_2. × 560.

FIG. 4. *O. cruciata*. Diagram of longitudinal section of a cylindrical protuberance. Bundle-ring, *b*; callus, *cl*; cortex, *cx*. × 25.

FIG. 5. *O. cruciata* The same as fig. 4. Group of callus cells from the apex. × 360.

FIG. 6. *O. cruciata*. The same as figs. 4 and 5. Drawing of portion of apex of bundle-ring opposite point marked *z* in fig. 4. Spiral ducts run transversely across the tip.

FIG. 7. *O. cruciata*. Diagram of longitudinal section of apex of plant shown in fig. 8. Sections of vegetative circle, *vc*; callus, *cl*; primary bundle ring, *b*. × 18¾.

FIG. 8. *O. cruciata*. Longitudinal section of apex of fig. 7 at *cl*. Callus, *cl*; protophloem, ph_1, ph_2; proto-xylem showing spiral ducts, *xy*. This is an early stage in the formation of a protuberance. × 360.

FIG. 9. *O. cruciata*. Diagram of cross-section of base of fasciated rosette which shows traces of injury. The oval shape of the pith shows the beginning of the flattening. Phellogen, *pg*; bark, *bk*; meristems in pith, *mm*; callus at point of inhibition of growth, *cl*. × 8.

FIG. 10. *O. cruciata*. Diagram of longitudinal section of bifurcated tip, showing position of callus, *cl*. At *q* the bundle-elements run irregularly in a confused tangle. *K* is a small protuberance. × 52.

FIG. 11. *O. cruciata*. Drawing of longitudinal section of apex similar to fig. 13. An incision surrounded by hypertrophy and meristematic divisions. The contents of the cavity are stained reddish purple. × 560.

FIG. 12. *O. cruciata*. The same as fig. 11. Cells in pith surrounding the lower end of incision. The blackened edges indicate purplish discoloration between the cells. The cells hypertrophy and close in around the incision without dividing. × 480.

FIG. 13. *O. cruciata*. Diagrammatic longitudinal section of an injured tip similar to the one pictured in figs. 11 and 12. The apex seems to be slightly fasciated, and the stem is bifurcated. *i*, injury. × 25.

FIG. 14. *O. cruciata*. Transverse section of early stage of ring-fasciation. The intercellular conditions indicate that it has been injured. *Cf.* fig. 12. *m*, two cells of the meristem. × 560.

FIG. 15. *O. cruciata*. Transverse sections of ring-fasciation in fig. 14 at a more advanced stage. Secondary bundle-ring, b_2. In the center of the pith is a cavity surrounded by hypertrophied cells and meristematic divisions. This is not the beginning of the lysigenous cavity of the ring, which occurs some sections above. × 430.

FIG. 16. Transverse section of flowering stem just below the point of fasciation, showing inhibition in the formation of wood at *xx*. × 25.

FIG. 17. *Raimannia odorata*. Cross-section of young bifuricated rosette, showing injury to cortex and inhibition in the development of the bundle-ring at *xx*. × 92.

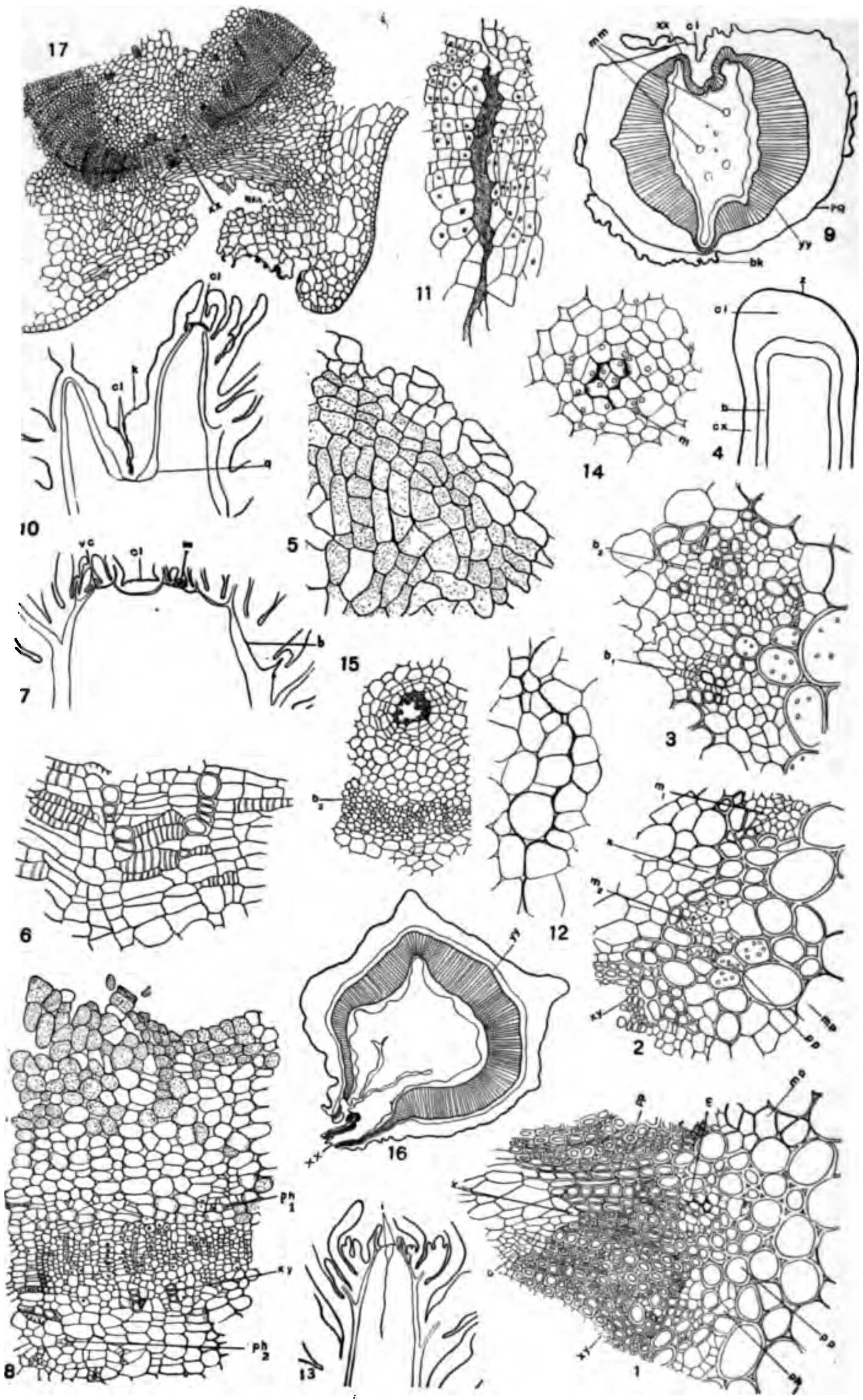

17
11
9
10
5
14
4
7
15
3
6
12
2
16
8
13
1

Plate 1

The White Sands, Otero Basin, New Mexico. The view is southwest toward the San Andreas Mountains. In foreground are parallel dunes with characteristic vegetation. (Reprinted from Publication No. 6.)

BOTANICAL FEATURES

OF

NORTH AMERICAN DESERTS

BY

DANIEL TREMBLY MacDOUGAL.

WASHINGTON, D. C.
Published by the Carnegie Institution of Washington
1908

CARNEGIE INSTITUTION OF WASHINGTON
Publication No. 99

Waverly Press
Williams & Wilkins Company
Baltimore, Md.

CONTENTS.

Botanical Features of North American Deserts.

INTRODUCTION.

Botanical science in its technical and applied branches has reached a stage of development in which it has become plainly evident that adequate progress in research in physiology, in comprehensions of life-histories, and in formulating the general principles governing the origin, environic relations and distributional movements of plants may be expected only by experimental methods in the field or in actual contact with the types of plants under consideration under normal environmental conditions.

In no part of the subject is this so imperative as in the study of the xerophytic and highly specialized forms characteristic of the desert regions of the world, which comprise a total area equal to that of a large continent. The aridity, widely ranging temperatures of soil and air, physical and chemical properties of the soils, conditions of insolation and radio-activity, together with the special forces modifying distribution, furnish a set of conditions not easily duplicated by the regulation of the artificial climates of glass-houses and not adequately represented by preserved material in herbaria and other collections. A European botanist of ability scarcely lays down his work at the end of a life of zeal and industry devoted to the study of the cacti under cultivation in a climate entirely foreign to them, when an examination of these peculiar forms in their native habitats reveals the necessity for a complete repetition of the entire investigation.

When the Carnegie Institution of Washington was established, Mr. Frederick V. Coville determined to present to it a plan for a Desert Botanical Laboratory. This long-cherished project was an outcome of his work in the Death Valley Expedition, in 1891. A plan was accordingly drawn up by him and presented to the Institution's Advisory Committee in Botany. This committee considered and approved it because it promised results concerning the fundamental processes of protoplasm as important as any in the whole realm of botany. The Board of Trustees of the Institution also gave their approval to it, and appropriated $8,000 for the establishment of such a laboratory and its maintenance for one year. Messrs. Coville and MacDougal were appointed by the Institution as an Advisory Board in relation to the matter. This Board decided to place the Laboratory under the immediate charge of a resident investigator, who should carry on researches under its guidance, and should be responsible to it in his relations to the Institution. It was

planned to begin a few inquiries of wide scope and important bearing to be carried on by the resident investigator until decisive results were obtained.

THE LABORATORY LOCATION TRIP.

Each member of the Advisory Board had visited, during the preceding twelve years, most of the more marked desert areas of the country. Nevertheless, it was deemed profitable to make, together, a systematic tour of these deserts, in order to gain a better comparative knowledge of the aspects of their vegetation and to select a locality offering the greatest advantages and facilities for the proposed work. Accordingly, between January 25 and February 28, 1903, they made a reconnaissance of the region along the Mexican boundary. As the outcome a site was selected on Tumamoc Mountain near Tucson, Arizona, and the erection of a laboratory building, according to plans approved by them, was begun. The organization of the laboratory was carried a step further by the appointment of Dr. W. A. Cannon as resident investigator.

In the absence of any publication dealing with the general features of American deserts, it seemed desirable to present the general results of observations made during the trip and include with them some of the information gained during previous work in deserts, illustrating the text with reproductions of landscapes showing characteristic vegetation. The paper embodying these features was brought out as publication No. 6 of the Institution in November, 1903.

The establishment of the Desert Laboratory and the continuance of the examination of the arid regions has made available a much greater amount of general information concerning the extent and character of the vegetation of such areas. The newer contributions concern the sage-brush deserts of the Great Basin, in Nevada and in Utah, the tropical deserts in southern Mexico, the arid depressed basins of the delta of the Colorado River, the Sonoran Desert, the Cucopa Mountains, and the desert of San Felipe de Jesus, in Baja California. The results of the explorations of Hedin, Pumpelly, Willis, MacMahon, and Huntington in Asia, and of other workers in Australia and Africa, together with the fuller data noted above, permit some more satisfactory generalizations than had been hitherto possible.

The edition of publication No. 6 (being the only attempt yet made to furnish a sketch of some of the characters of American deserts) having been exhausted, it has been thought advisable to include such portion of it within the present volume as might be necessary for completeness. This interpolation is made without special indication of the repetition, except in the plates. The character of the investigations taken up in connection with the main subject is fairly indicated by the work described in the next section.

EARLIER INVESTIGATIONS AND DEVELOPMENT OF DEPARTMENT OF BOTANICAL RESEARCH.

Upon taking up his duties at the Desert Laboratory in September, 1903, Dr. W. A. Cannon began the investigation of certain problems involving study of the relation of plants to atmospheric moisture, in which some notable improvements in methods and some important results were obtained in the next two years, as indicated by the titles published in the Year Books of the Institution. Incidentally, attention was also paid by him to the morphology and physiology of phanerogamic parasites, which are found in some abundance in the desert, and to other specializations in root-structure for water-storage and in chlorophyl distribution in shoots.

Prof. V. M. Spalding was granted the privileges of the Laboratory late in 1903, and also carried on some work upon the relations of shoots to atmospheric moisture. Later he began a systematic study of the distribution of desert plants, and in accordance with a comprehensive plan was given a series of grants to extend his work, in which notable progress has been accomplished in some of the major problems presented. Mrs. E. S. Spalding was also given the privileges of the Laboratory in 1903, and has taken up an investigation of certain features of water-storage by cacti and succulents of the region contiguous to the Laboratory.

Dr. B. E. Livingston was given a grant in 1904 for carrying out an investigation of the relation of plants to soil moisture, and spent the summer of that year in residence at the Laboratory. The results obtained are embodied in publication No. 50.

Prof. Francis E. Lloyd, Teachers' College, Columbia University, was given the privileges of the Laboratory in 1904 for the purpose of carrying out an investigation upon the physiology of stomata, which had been subsidized by the Botanical Society of America. In the following year this work was continued under a grant from the Institution, and has now been brought to completion and the results published as publication No. 82.

Mr. Frederick V. Coville, of the U. S. Department of Agriculture, continued an investigation of the drink plants of the North American Indians, which had been begun during the Laboratory location trip, and the results of his work were published by the Smithsonian Institution.

Dr. D. T. MacDougal, of the New York Botanical Garden, carried out various pieces of explorational work, paying attention to observations on distribution, ecology, and desert topography in Texas, in the vicinity of the Colorado River, from The Needles to the Gulf of California, around the mud volcanoes of this region, in the Cucopa Mountains, and in the Salton and Pattie basins, the results of which have been brought out in various publications. In much of this field-work Mr.

Godfrey Sykes, of Flagstaff, Arizona, participated, and an authentic map of the delta and contiguous regions was prepared, which was published in 1905, the principal features of which are reproduced in plate 34.

Workers in several branches of science have visited Tucson for limited periods and used the facilities of the Laboratory for securing desired information concerning their special researches.

It was deemed desirable to correlate the work being carried on at the Desert Laboratory with the other botanical investigations of the Institution, and by act of the Trustees on December 18, 1905, the Department of Botanical Research was created, with Dr. D. T. MacDougal as director. The staff of the station was constituted of Dr. W. A. Cannon, Dr. B. E. Livingston, Prof. V. M. Spalding, and Mr. Godfrey Sykes; and Prof. F. E. Lloyd was appointed for one year to complete his work upon stomata.

In accordance with the newly formed plans, the Desert Laboratory, at first established to carry on certain special investigations, was made the headquarters of the department and, so far as possible, the efforts of the members of the staff not resident at Tucson were brought into correlation with the activities of the Laboratory.

The reorganized staff assembled early in 1906 and operations were begun at once by which the capacity of the Laboratory was doubled, a greenhouse was erected, a new pumping-plant and reservoir for well-water and rain-water constructed, and a wire fence was thrown around the principal tract of the domain of the Laboratory. By the acquisition of controlling titles, the tract of land originally given to the Institution for the use of the Laboratory in 1903 was increased to 860 acres, including nearly the whole of Tumamoc Hill and a large area of mesa-like slope to the westward.

In addition to the individual researches undertaken by the various members of the staff, other questions arise in the activity of a laboratory of this kind which require the combined and organized effort of the entire staff for a term of years. Work of such character demands the utmost exactness and fullness of records, in which the observations and experimental results are interpreted in the broadest general manner. Furthermore, it is important that such work should be begun by adequate methods, and that it cover possible developments in advanced stages of the work, if the results obtained are to be commensurate with the total effort expended.

A group of problems of this character was offered by the depressed basins which form a part of the delta of the Colorado River and which have an exceedingly arid climate.

Much of the more pronounced desert of North America has been in submersion during comparatively recent geological periods, and consequently the origin and distribution of the highly specialized flora which inhabits such regions have resulted from forces which may now be studied

Plate 2

Column in White Sands. Shade and mechanical action of roots of three-leaved sumac have prevented a section of a dune from being moved by action of the sun and wind, and it remains in columnar form.

Plate 3

Area left bare by dune which has moved to the right, and out of the view. Advancing dunes on left. Grama grass (*Bouteloua*) on level space in foreground.

Water-hole in the White Sands, Otero Basin, New Mexico. The water is locally known as "gyp" water. A group of cottonwoods (*Populus*) are shown in background on the right. (Reprinted from Publication No. 6.)

Tree yucca (*Yucca radiosa*) in Otero basin, New Mexico. The large plant still bears emptied pods of previous season, and the bases of dead and weathered leaves on the lower part of the stem. The two smaller plants are specimens of the same species. (Reprinted from Publication No. 6.)

in action in the Salton and Pattie basins, which are filled with water at long and irregular intervals.

The Salton Basin is an irregular oblong depression with an area of 2,000 square miles, having its long axis lying northwest and southeast, extending from the angle formed by the San Jacinto Mountains and San Bernardino foothills, in California, to a point across the international boundary line between the United States and Mexico, being cut off from the Gulf of California by the alluvial deposits in the delta of the Colorado River. The lowest part of this depression is 287 feet below sea-level, and the presence of an old beach-line several feet above sea-level shows that comparatively recently it has been the site of a lake which emptied southwardly into the Gulf of California. Within historic times, however, the basin has been empty, and this great bowl is one of the marked features of the Colorado Desert. The rainfall is exceedingly scanty and the soil is highly charged with salts of various kinds; consequently the vegetation is of a pronounced spinose or halophytic type.

Several times within the last century the flood-waters of the Rio Colorado have been diverted to such an extent as to flow into the basin and form a small lake, and the presence of several minor beach-lines on the slopes of the basin suggests that such inflows have taken place repeatedly within the last few thousand years, and also that the level of the ancient lake was not lowered uniformly.

During the last three years faulty engineering operations opened a channel leading into the basin, and the result was that the main flow of the Colorado River ran into the depression and a lake with an area of 500 square miles was formed, accompanied, of course, by the entire destruction of the desert vegetation on this area. The commercial interests imperiled, together with the history of the previous inflows, leads to the belief that we may soon have available the spectacle of the drying up of this lake and the advance of the desert vegetation to reoccupy the areas left bare by the recession of the water. As a fortunate prelude or beginning of this study, Dr. D. T. MacDougal and Mr. Frederick V. Coville visited the basin in 1903 and made some observations upon the vegetation, together with some photographs of the manner of occurrence and habit of several of the more important native forms. The evaporation and seepage in the region are such that at least ten or twelve years will be necessary to empty the basin or reduce it to a minimum, which will thus afford experimental conditions on a large scale of the revegetation of a submerged area by xerophytic plants.

The Pattie Basin, which is connected with the lower portion of the delta around the southern end of the Cucopa Mountains, also received some of the flood, and the body of water formed, the Laguna Maquata, has had a more nearly continuous existence, being entirely dried up only occasionally. It is, in fact, repeating the earlier history of the lake in

the Salton Basin, and the study of the conditions in the two localities contemporaneously may confidently be expected to yield results of great value.

An examination of the effect of the advancing shore-line upon desert vegetation was made in May, 1906, and a more serious expedition was made to both basins in February, 1907, in which areas were selected and surveyed for detailed investigation as to the conditions of soil moisture, salt content, and physical factors of the soil, together with the movements and development of plant societies.

Another general problem requiring the focused effort of the Laboratory is comprised in the influence of altitude and climatic factors upon vegetation with respect to the direct reactions by which individual adaptation is accomplished and to possible alterations in the transmission of hereditary qualities.

As a result of various horticultural and agricultural activities and of the constant interchange of living material which has taken place among botanical gardens and other collections of living plants, assembled for observational purposes, a large number of species have been transferred from one country to another, and some observations as to alterations in habit and form resulting from such removals are recorded. A few experimental tests have been made in the cultivation of species through a range of altitude and some of the morphological changes induced have been described. It is known that the color, time of bloom, habit, structure of the root and shoot, general aspect of plants, and economic value may be greatly altered by cultures at various altitudes, but no systematic tests have been made to determine to what factors in the climate these differences are due. The solutions of the problems involved would settle some of the most important problems in general physiology and would also go far in enabling us to account for the structure and form of the species of which the vegetation of the earth is composed.

It is by means of experimental observations of this kind that it also may be hoped to obtain evidence as to the inheritance of somatic variations, a question which has been a much vexed one for many years. No adequate tests have yet been made to ascertain whether or not the marked changes induced in plants by cultivations at altitudes higher or lower than the normal are fully transmissible to succeeding generations grown under other conditions.

The practical problems of acclimatization offer some highly peculiar conditions. Thus, two separated localities may offer meteorological conditions apparently similar, so far as ordinary methods of weather records show, yet the exchange of plants between the two places will be attended with but indifferent success, even when differences in composition of the soil are accounted for. It seems unnecessary to point out that when the factors in climate have been accurately analyzed as to their effect upon

vegetation a much more rational basis will be afforded for efforts at acclimatization.

A small plantation has been established in the grounds of the Laboratory in the alluvial valley of the Santa Cruz River at an elevation of 2,100 feet, with a rainfall averaging 12 inches; and a second on the slopes of the Santa Catalina Mountains, in an arid locality at an elevation of about 5,400 feet. A third series of experimental cultures has been installed in Marshall Gulch, on the southern slopes of Mount Lemon, the culminating peak of the range, at an elevation of about 8,000 feet. The rainfall in the last-named locality is such that the vegetation is of a distinctly mesophytic character. Steps are taken to obtain thermometric and other data which will allow an analysis of the climate in all of the localities named. Several years will be necessary before any definite conclusions may be drawn from the results of these cultures, which, however, already present some new and striking facts.

DESERT REGIONS OF NORTH AMERICA.

TRANSITION FROM THE HUMID REGIONS TO THE CHIHUAHUA DESERT, IN WESTERN TEXAS.

An analysis of the conditions to be met in this vast region, based upon an actual survey, has recently been made by Professor Bray (Vegetation of the Sotol Country, Bulletin of the University of Texas, Scientific Series No. 6, 1905), and the general results are set forth in the following paragraphs, collated from his paper on the subject:

Eastern Texas has the characteristic humid and warm-temperate flora of the Gulf region, with the long-leaf pine (*Pinus palustris*), the cane (*Arundinaria*), bald cypress (*Taxodium distichum*), and associated species, with a rainfall of over 50 inches annually. Passing westward from the Sabine River, by well-marked steps, a pronounced xerophytic aspect of the vegetation is encountered west of San Antonio, 300 miles from the starting-point, and the desert character of the flora becomes very marked in the sotol country, 200 miles farther west, and takes on increased aridity in the region of El Paso, in the Chihuahuan Desert, with a rainfall of about 10 inches yearly.

Orange, on the Sabine River, has an elevation of only 12 feet above the sea-level and an annual rainfall of about 50 inches. The region comprises a flat coastal plain, with low sandy ridges, river bottoms, and bayous. The vegetation includes cane (*Arundinaria*) and reed swamps; humid subtropical bottom-land forests, with magnolias, bay, pecan, hollies, oaks, gums; dense cypress and tupelo swamp forest, thickets of palmetto (*Sabal glabra*); heavy forests of long-leaf pine and of loblolly pine.

Houston, 60 miles to the westward of Orange, rises but 40 feet above sea-level and shows a slightly smaller amount of rainfall, the annual pre-

cipitation being 45 inches. The country may be considered as an extension of the Coastal Plain, with sand ridges higher than at Orange and with well-defined drainage channels. The western border of the Atlantic type of continuous forest is to be found in this region; also of the southern pine. Coastal prairie areas are included, bearing wet-soil grasses, rushes, sedges, and many prairie annuals. Marshes are found in which occur the spider lily and *Daubentia longifolia*.

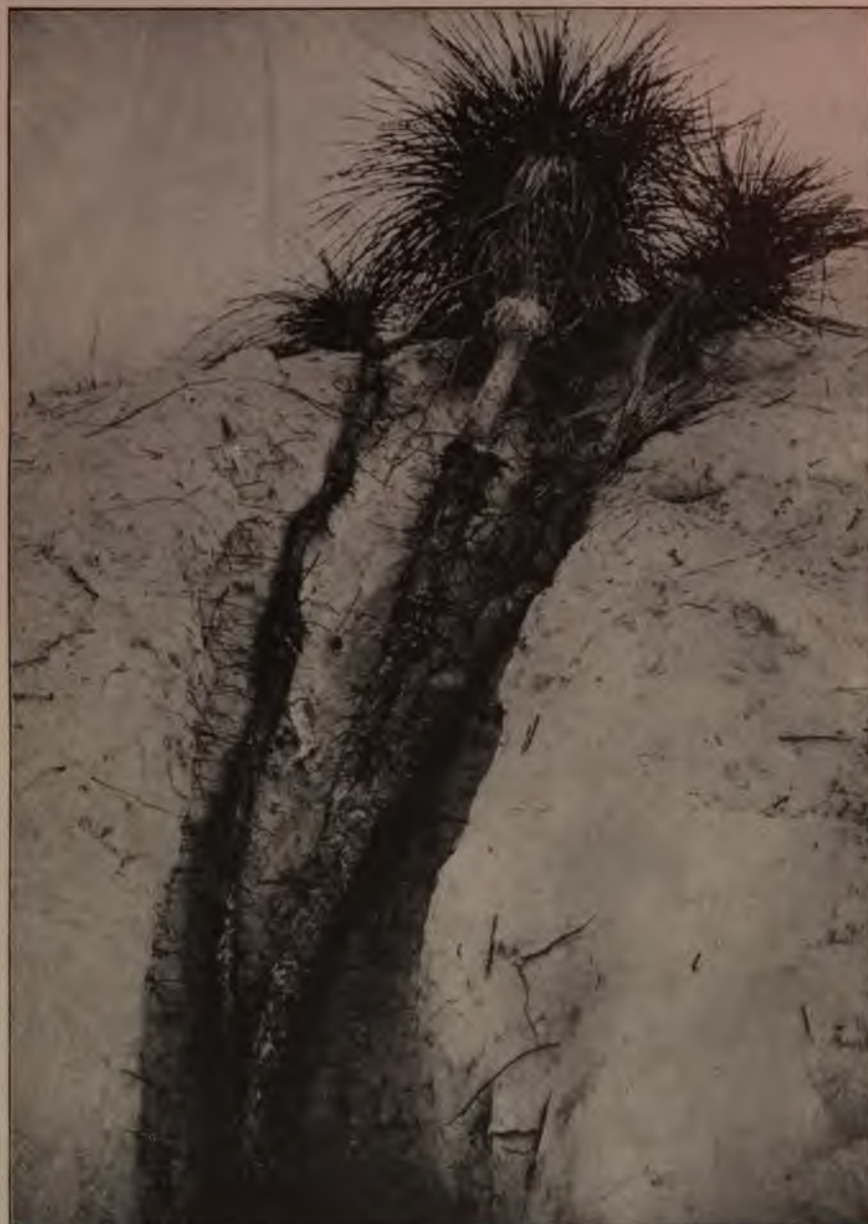
Luling, 260 miles west of Orange, is 416 feet above sea-level and has an annual precipitation of about 33 inches. The region has a rolling surface, the soils being sandy loam, gravelly clay, and rich alluvial bottom-lands, and shows many wide expanses of grass-land with an abundance of prairie annuals.

Numerous sandy and gravelly soil species are found, among which are *Indigofera leptosepala*, *Crusea allococca*, *Callirhoe involucrata*, *Meriolix serrulata*, *Aphanostephus arkansanus*, *Sida lindheimeri*, *Allionia nyctaginea*, *Berlandiera lyrata*, and several species of cacti; e. g., *Opuntia lindheimeri*, *O. leptocaulis*, *Echinocereus cæspitosus*, and *Cactus heyderi*.

San Antonio is 316 miles west of Orange, at an elevation of 686 feet, and has an annual precipitation of about 29 inches. This place marks with fair distinctness the inner border of the Rio Grande plain, with slightly rolling surface and deep porous soils, and the southern margin of the Great Plains area, with the roughly eroded escarpment of the Edwards Plateau limestone.

On the one hand, Gulfward, the Rio Grande plain contains a thoroughly lower Sonoran flora, of which woody species are the most obvious, constituting the widely known chaparral, which here, however, is scarcely typical, being of too luxuriant growth; e. g., the mesquite, which is most abundant, being a tree 15 to 20 feet tall. The Mimosæ begin to dominate here, notably mesquite, *Acacia farnesiana*, *A. wrightii*, *A. amentacea*; brasil, *Zizyphus;* much *Opuntia engelmanni* and *O. leptocaulis*, *Lippia* (*Aloysia*) *ligustrina*, all of which become more abundant west of the Sabinal; grasses of the western plains and more of the northern plains annuals; *Yucca rupicola* and *treculeana*. On the other hand are the limestone hills, marking the dissected margin of the Great Plains region in a xerophytic timber vegetation with extensive cedar brakes (*Juniperus sabinoides*), mountain forms of live-oak and hackberry, shin-oak (*Quercus breviloba*), cedar-elm (*Ulmus crassifolia*), *Ungnadia speciosa*, *Brayodendron texanum*, etc., being notably a timber vegetation with modified Atlantic forest species mixed with typical lower (and sometimes upper) Sonoran species; e. g., madroña (*Arbutus xalapensis*).

Spofford (Fort Clark) is 449 miles west of Orange, at an elevation of 1,015 feet and with an annual precipitation of 24 inches. This is also on the northern border of the Rio Grande plain, and is characterized by rolling gravelly ridges and intervening flats with finer soils.

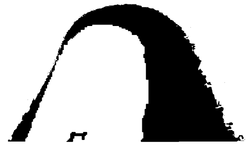


Yucca radiosa which has elongated its stem sufficiently to keep its crown above a moving gypsum dune, the crest of which has passed it a few feet. The excavation has laid bare a trunk twice the ordinary length. White Sands, New Mexico. (Reprinted from Publication No. 6.)

Steep slope of granite foothill in the Sierritas, covered with sotol. A flood has recently descended the streamway, uprooted the palo verde and mesquite, and cut into the alluvial deposit on the farther bank.

Vegetation of the Sonora desert near Torres, Mexico. The cactus on the left is the pitahaya (*Cereus thurberi*), about 20 feet high; the one on the right is *Cereus schottii*. (Reprinted from Publication No. 6.)

Yaqui Indian family and dwelling at El Rancho, west of Torres, Mexico. At the right stands a Papago Indian guide. At the left is the Yaqui family, father, mother and two daughters. Two palo fierro trees (*Olneya tesota*) are in background. (Reprinted from Publication No. 6.)



The more xerophytic chaparral species are in evidence here; e. g., *Leucophyllum texanum*, *Microrhamnus ericoides*, *Karwinskia humboldtiana*, *Celtis pallida*, *Kœberlinia spinosa*, *Acacia constricta*, *A. berlandieri* (the huajilla), *Leucæna retusa* (also, of course, the mesquite), *Acacia amentacea* and *wrightii*, and *Mimosa fragrans* (of farther east); occasional specimens of Mexican greasewood (*Covillea tridentata*), *Krameria canescens* and *ramosissima*, *Yucca treculeana*, etc.

Del Rio is 486 miles west of Orange, at an elevation of 956 feet, and although but a short distance from Spofford has a rainfall markedly less, the annual amount being on an average but 20 inches. This place lies in the alluvial valley of the Rio Grande and near the rough margin of the Edwards Plateau. Ridges with coarse limestone fragments and flats with calcareous clay and alluvial soils are included. Near here begins the arid, rocky, débris-covered country, to be included in the Chihuahuan Desert, which becomes emphasized a short distance to the westward, between Devil's River and the Pecos, where sotol, ocotillo, lechuguilla, and cacti begin to predominate.

The region shows areas of short open chaparral, with broken stretches of grass-land, or rather areas bearing bunchy grasses, while huajilla, *Leucophyllum*, *Parkinsonia texana*, and various species of *Opuntia* are abundant.

Langtry is 550 miles west of Orange, at an elevation of 1,321 feet, and has an annual precipitation of but 15 inches. It lies near the canyon of the Rio Grande, the surrounding country including many of its branches, as well as high, gracefully sloping hills, wide draws, and broad divides, with coarse and fine débris of limestone everywhere. This is the typical sotol region, and the sotol (*Dasylirion texanum*) abounds on the broad divides, while the lechuguilla (*Agave lechuguilla*) occurs in abundance on the hilltops and slopes. Dwarf chaparral shrubs, *Covillea*, *Flourensia cernua*, *Microrhamnus ericoides*, *Parosela formosa*, *Ephedra antisyphilitica*, *Jatropha spathulata*, *Acacia constricta* and *A. greggii*, *Krameria*, *Lycium*, *Mortonia*, *Fouquieria splendens*, and the following cacti are found: *Echinocereus cæspitosus*, *E. dasyacanthus*, *E. paucispinus*, *E. longispinus*, *Opuntia arborescens*, *O. arenaria*, *O. engelmanni*, *O. leptocaulis*, *Ariocarpus fissuratus*, *Echinocactus brevihamatus*, *E. horizontalonius*, *E. longihamatus*, *E. setispinus*, *E. texensis*, *Lophophora williamsii*, *Cactus conimamma*, *C. heyderi*, *C. micromeris*, *C. pectinatus*, *C. pusillus*, *C. scolymoides*, *C. viviparus*, *C. dubius*, and *Cereus greggii*.

Haymond is 668 miles west from Orange, at an elevation of 3,883 feet, and has an annual precipitation of about 15 inches. The region here is a high, gently rolling plateau, bearing isolated mountains. The soil is fine, deep, and the surface of the ground is windswept. This marks the western border of the sotol region and the edge of a grass-covered area, the cylindrical opuntias being abundant.

Marfa is 743 miles west from Orange, at an elevation of 4,692 feet, with a rainfall of about 19 inches yearly. This lies on a level plateau with fine loose soil and with isolated mountain masses, and is a typical "short-grass" country. Prairie annuals are numerous and abundant and *Kœberlinia* and *Yucca radiosa* are found. Among the annuals are *Asclepias latifolia*, *A. tuberosa*, *Astragalus mollissimus* and *A. caryocarpus*, *Psoralea linearifolia* and *P. digitata*, *Hoffmanseggia jamesii*, and *Meriolix intermedia*.

El Paso is 939 miles west from Orange, at an elevation of 3,718 feet, and receives an annual precipitation of about 10 inches.

The region here includes the valley of the Rio Grande, with its numerous forms adapted to the dry air and rooting in the alluvium, and *Covillea*, *Sarcobatus*, *Fouquieria*, *Croton*, many cacti, shrubby composites, scattered grasses, and other xerophilous forms on the mesas.

Of the various separable regions in the transition from the humid to the arid areas of the West, that bearing the sotol bears a vegetation of marked xerophytic type and is true desert. Since the sotol region is one in which the physiographic factor is a determinative one, it is possible to delimit it with some accuracy.

In Texas the main body of the sotol country is embraced in the rough limestone region lying between the breaks of the Devil's River and the front ranges of the Cordilleras near Marathon, over 150 miles west, extending thence southwestward over the region of the great bend of the Rio Grande. Northward, tongues of the sotol formation reach out along the divides of the drainage area of the Devil's River into the Edwards Plateau, and of the Pecos River into the Stockton Plateau, and farther westward the formation follows the foothills and eastern front of the mountains into southern New Mexico. Westward to the Rio Grande at Presidio and El Paso the sotol formation occurs wherever the physiographic features with which it is identified are repeated, viz., débris-covered mountain slopes and rolling or hilly areas representing the progress of dissection of the plateaus.

The lechuguilla is almost as widely abundant as the sotol in this region, and has been estimated to cover more or less densely an area of 20,000 square miles. The distance across this sotol-lechuguilla belt where it is crossed by the Southern Pacific Railway from east to west is about 150 miles.

THE SAND-DUNES OF CHIHUAHUA.

South of El Paso and crossed by the old traders' trail from the settlement of Santa Fé to the city of Chihuahua is a long stretch of sand-dunes known locally as Los Medanos (supposedly a modification of Los Meganos). Necessarily these were known to the earlier travelers, as evinced by the following apt description by J. R. Bartlett, "Personal Narrative," etc., 1854).

He says:

> The *Medanos*, or Sandhills, are a peculiar feature in this country, stretching in a line from northwest to southeast for some twenty miles, as far as I could judge. Nearly destitute of vegetation, their light yellow or whitish appearance presents a strong contrast to the deep brown of the adjacent mountains, which form the background of the landscape. The sand is very light and fine and forms deep ridges resembling the large waves of the ocean. When the wind blows, this sand is set in motion, filling up the former valleys and forming new drifts or hills. The road is then entirely obliterated, not a footprint or a wagon-rut being left to show the direction. Two miles brought us to the spring known as Samalayuca (Ojo de Samalayuca). It is a complete oasis in the desert, and consists of a small pool of water, in and around which are bushes and trees. It seems to be placed here by nature for the weary and thirsty traveler, by whom the route would else be impassable. On the west there is not usually any water nearer than the Salado, thirty miles distant, which is also the distance of El Paso, the nearest point to the north. Eastward is San Elizario, twenty miles.

Since these dunes seemed to be unfamiliar to botanists of to-day, a brief visit was made to them by Messrs. Coville and MacDougal, and to the region between Samalayuca and a point 6 miles to the southward.

The dunes, where the railroad crosses them, are about 40 feet high, with scant winter vegetation consisting of a few woody plants, principally a labiate bush (*Poliomintha incana*), an *Artemisia*, a *Chrysothamnus*, *Yucca radiosa*), and a suffrutescent *Senecio*. Two perennial grasses, an *Andropogon* and a *Sporobolus* with a spike-like panicle (*Sporobolus cryspiandrus*), are of frequent occurrence, as are the remnants of many annual plants. The *Yucca* takes an important part in binding the sands; roots were seen extending in a nearly horizontal direction 40 feet from the plant.

From the dunes toward Samalayuca the valley bottom has vegetation of mesquite mixed with *Zizyphus*, *Kœberlinia spinosa*, and *Atriplex canescens*. An annual *Croton* forms a thick, spindle-shaped tumbleweed adapted for rolling along one axis.

The highest part of the dunes is not crossed by the railroad, but lies east and southeast from Samalayuca about 5 miles and apparently rises 200 feet from the plain.

About 9 pounds of the material of which the dunes were composed was collected by removing a thin surface layer and then placing it in a cloth waterproof bag. This material was forwarded to Dr. W. J. Gies, consulting chemist to the New York Botanical Garden, with the request for an analysis. The results obtained by him are found on pages 16 and 17 of this paper.

THE OTERO BASIN.

Extending northward for nearly 100 miles from El Paso is the noted Jornada del Muerto (Journey of Death), which has a width of 30 to 40 miles. It formed a portion of the route connecting the earliest settlements along the Rio Grande, and here the traveler was compelled to

leave the stream far to the westward, in its deeply cut, inaccessible canyon, and toil for two or three days in the burning heat without water, except such as might be carried. It was for three centuries one of the most menacing and hazardous overland journeys to be encountered in the American Desert. Recent investigations, however, have shown that the region traversed is in reality a basin, and that water is to be found, as in many other deserts, within a reasonable distance of the surface.

The San Andreas Mountains form part of the eastern boundary of this basin, and beyond lies an equally remarkable desert, that of the Otero basin. This basin lies with its longer axis in a north and south direction, bounded on the east by the White and Sacramento Mountains and on the west by the San Andreas and Oscuro Mountains. Once the bed of an ancient lake, it has had a complicated geological history. A lava-flow extends without interruption for 50 miles east of the Oscuro Mountains, and this or other causes must have interrupted the great stream which may have flowed southward through the basin, expanding into a lake with varying dimensions as the conditions varied from humid to arid in the alternation of climate, which has finally brought it to a condition at the present time in which the rainfall is scarcely a dozen inches. The ancient Lake Otero probably began its existence in the Tertiary times and must have occupied an area of nearly 2,000 square miles, and a vertical section by means of well-bores shows a very heavy sedimentary deposit. The oscillation of this body of water carried its dissolved salts through various stages of concentration even to complete precipitation, and the beds of material thus laid down were covered by later deposits of sediment. The fact that different salts are precipitated at different degrees of saturation accounts for the deposition of the various saline compounds separately. More modern erosion cuts these deposits in places and lays them bare in others. Thus the intermittent streams which come down from the mountain canyons cut into and bring down in solution some of the ancient deposits, which are carried out toward the center of the basin and laid down again by evaporation in the level floor-like playas. In some places the drainage water percolates down through an inclined deposit and comes to the surface as a salt spring which builds up a cone-shaped deposit around its vent. (C. L. Herrick, Lake Otero, an ancient salt lake basin in southeastern New Mexico, Amer. Geol. vol. 34, p. 174, 1904).

As a result of the interplay of a complex series of geological factors, the central portion of this basin to-day shows some highly characteristic desert features, among which are to be reckoned the great salt and soda flat in the western portion, the salt lake southwest from Alamogordo, and most striking of all, the "White Sands," an area of about 300 square miles covered with dunes of gypsum sand rising to a maximum height of 60 feet.

Guarequi (*Ibervillea sonoræ*) under a clump of large opuntias. The large expanded stem-base, which serves as a storage organ, lies almost entirely above the surface of the ground. (Reprinted from Publication No. 6.)

Water jars (ollas) at a Yaqui dwelling, west of Torres, Mexico. One of them is on a stump of palo verde. Under it are three shoots of Indian corn, irrigated by the drippings. (Reprinted from Publication No. 6.)

Desert island in Guaymas bay, Mexico. The large cactus is *Cereus pringlei*. There is a fringe of mangrove (*Avicennia* and *Rhizophora*) along the beach. (Reprinted from Publication No. 6.)

The surface of the dunes is sparkling white, due to the dry condition of the gypsum powder, but a few inches beneath it is of a yellowish or buff color and is distinctly moist and cool to the touch, even when the air is extremely hot. The smallest particles may be crumbled in the fingers, and as a consequence the dunes are solidly packed except on newly forming steep slopes (plate 1).

The most characteristic plant of the dunes is the three-leaf sumac (*Rhus trilobata*), which occurs in the form of single hemispherical bushes 4 to 8 feet high, the lower branches hugging the sand. The plant grows vigorously, the trunk at or beneath the surface often reaching a diameter of 3 inches. The binding and protecting effect of this bush is often shown in a striking manner when in the cutting down of an older dune by the wind a column of sand may be left protected above from the sun by the close covering of the branches and leaves, and the sand in the column itself bound together by the long penetrating roots. An incrustation, apparently of gypsum, is often found on dead roots. One of these columns was about 15 feet high from its base to the summit of the protecting bush and about 8 feet in diameter at the base (plate 2). A curious fact brought out in the denudation of the underground trunks of this plant by the shifting of the dunes is the abundant exudation of a pale amber gum with the characteristic aroma of the crushed twigs. This, mixing with the sand, forms hard, honeycombed masses sometimes 3 inches in diameter.

Other characteristic woody plants of the dunes are *Atriplex canescens*, two species of *Chrysothamnus*, and *Yucca radiosa*. The underground trunks of the *Atriplex* often attain a diameter of 4 inches, those of the *Yucca* 6 inches. A marked peculiarity of the White Sands is that a cottonwood is occasionally found in the lower dunes, reaching a foot in diameter, but seldom more than 15 feet in height; yet at the same time not a mesquite was seen. The mesquite is a tree requiring less moisture than the cottonwood. Apparently the presence of an excess of gypsum is prejudicial to the growth of the mesquite.

The bottoms among the dunes have a dense vegetation as compared with that of the dunes themselves. It is characterized especially by the presence of a grama grass (*Bouteloua*), forming almost a turf, and by frequent clumps of *Ephedra* of a grayish purple color at this season and with 3-scaled nodes (plate 3). These bottoms usually show no sign of moisture, but in two places we found water-holes, the water so alkaline that the horses would not drink it at the end of their first day's drive. About both holes occurred the salt-grass (*Distichlis spicata*) and wire-grass (*Juncus balticus*), both of them characteristic of moist alkaline soils (plate 4).

The relation of *Yucca radiosa* to the sand dunes is unusually interesting. A group of four small yucca shoots standing about 3 feet high to the tip of the highest leaf was found upon the summit ridge of a 30-

foot dune. We dug the trunk out to a depth of 14 feet. All four plants were from branches of the same trunk, the lowest branch arising about 16 feet from the base of the dune; the main trunk and the branches bore marks of rosettes of leaves at intervals all the way to the lowest point reached. The trunk was thicker here, about 4 inches, than at any point above. The strata in the cut showed that the yucca once stood on the front slope of the dune. The trunk sloped in the direction in which the dune was moving. In the plain in front of the dunes were occasional low plants of the same species of yucca. Considering all the evidence, the conclusion is irresistible that the yucca originally grew on the plain, was engulfed by the sand, and gradually grew through each successive layer of sand that drifted over it until the summit of the dune was reached. In the vicinity, at the rear of the dune, were other long trunks partly denuded by the passing of the dune (plates 5 and 6).

The greatest flow of air over the dunes is from the southwest, yet other winds are strong enough to complicate the movements of the dunes. The major motion appears to be in an easterly or northeasterly direction, and places are found where the eastern margin of the white sands have advanced a mile within 20 years, although it is not to be taken for granted that the entire mass has such absolute annual rate of movement. The occupancy of a portion of the soil by a dune changes its physical qualities and leaves behind it such infiltrated material that when left bare a different series of plants finds a foothold, as was found by numerous observations.

Analyses of Sands.—The following report on the gypsum sand from the White Sands of the Otero Basin and on sand from the Chihuahuan Desert has been made by Dr. William J. Gies:

I present herewith the results of my chemical analyses of the two samples of sand expressed by you to me from Tucson, Arizona, on February 16 and received by me on February 24:

SAMPLE I. LOCALITY: OTERO BASIN, NEW MEXICO.

General Description.—Color white to delicate cream, with occasional very minute black particles. There were also a few reddish and yellowish-red grains. Now and then red specks could be detected in the white grains. Glassy grains of silica were present. Nearly all the grains were very small, about the size of those in ordinary sea sand. A few larger masses were made up of many of the small grains cemented or fused together. These masses were more cream-colored than the small grains; some contained a dark nucleus. They varied in size from such as were only three or four times the bulk of the uniformly small grains to a few which were nearly as large as a pea. No special crystalline qualities were observed in any sample of the sand. The grains were angular or rounded by erosion. Fragments of elytra of beetles were detected and occasional pieces of hair and small splinters were also seen.

Before subjecting the sand to anaylsis it was passed through a copper sieve the meshes of which were just large enough to permit the passage of the typical and uniformly sized grains. Only a few grams of material, consisting of the larger fused particles, elytra of beetles, hair, etc., were separated in this way from four kilos of

the sand as received. All of this material was regarded as extraneous matter, and only the main bulk of the sand was analyzed quantitatively.

Qualitative Data.—The sand dissolved readily in water and in dilute acids, leaving only a slight residue of silicious matter. The black particles in the sand seemed to be entirely insoluble in these media. The aqueous solution was neutral to litmus. The hydrochloric acid solution was slightly yellowish in color, due doubtless to the presence of iron. On diluting the hot concentrated sulphuric acid solution, crystals of calcium sulphate quickly separated. On igniting the sand it immediately blanched, and abundance of water was evolved, but the sand did not fuse, even in platinum, over a blowpipe. Extraction of the ignited sand in water gave a solution slightly alkaline in reaction. Only a minute trace of carbonic acid gas could be produced from the sand on ignition, a fact showing that practically no organic matter is contained in it. Such organic matter as was actually present in the few particles separated from the sand consists, as already stated, of the fragments of insects, excreta of animals, etc., and is too slight in quantity to have much significance as nutrient material for plants.

On drying a sample of the sand in an air-bath at 100° C. it soon became translucent and finally snow white. The grains retained their original shape. Water of crystallization was eliminated in abundance. The sand contains traces of sodium phosphate and chloride. The larger particles removed with the sieve contained a more decided quantity of chlorine, 0.7 to 0.9 per cent.

Quantitative Analysis.—Preliminary Data.

A. Sand dried in an air bath at 30° to 35° C.:

(*a*) On drying a constant weight in an air-bath at 110° to 120° C. the quantity of water eliminated was 19.9 per cent.

(*b*) On drying to constant weight in an air-bath at 50° to 60° C. the weight of the substance remained the same.

(*c*) On continuous percolation at room temperature of small quantities of distilled water at a time over the sand, until about 100 parts water to 1 of sand was used, 79.9 per cent of the sand was dissolved and only 20.1 per cent of it remained as residue. The latter was still dissolving when the experiment was discontinued and further percolation would have reduced the amount of residue (see under *B*, (*b*) 4 below).

(*d*) On continuous percolation, as above, with distilled water at 30° C. the dissolved matter amounted to 87.1 per cent and the residue to only 12.9 per cent. Further percolation would have decreased the weight of the residue (see under *B*, (*b*) 3 below).

B. Sand dried in an air-bath at 110° to 120° C.:

(*a*) On ignition in a platinum crucible over a blowpipe the loss of weight was 1.1 per cent.

(*b*) On treatment for three hours with about 1 liter of hot acids, hot water, or cold water per gram of substance the following data were obtained:

	Solvent.	Substance dissolved.	Residue.
		P. ct.	*P. ct.*
1	One part NCl and three parts H_2O	97.4	2.6
2	Two parts HNO_3 and two parts H_2O	97.8	2.2
3	Boiling H_2O	94.3*	5.7
4	Cold H_2O (15° C.)	96.4	3.6

*Calcium sulphate is more soluble in cold than in hot water.

Some General Deductions.—The analytic results set forth in the above table and in the one given below show that the sand is mainly composed of grains of calcium sulphate derived from crystalline gypsum. Silica and also silicate of iron and aluminum are present in small amounts. Insignificant quantities of soluble substances such as chloride (probably of calcium) may also be detected.

The sand is free from nitrogenous matter, except such minute amounts of animal débris and excreta as have already been referred to.

Percentage Composition. (Sand dried at 30° to 35° C. and at 110° to 120° C.)

	I.	II.	Average.	Average.
	P. ct.	*P. ct.*	*P. ct.*	*P. ct.*
CaO	30.4	31.2	30.8	38.5
SO_3	44.5	43.9	44.2	55.1
SiO_2	2.8	2.6	2.7	3.4
Al_2O_3, Fe_2O_3	0.4	0.4	0.4	0.5
H_2O	....	20.8	20.8	1.1
Traces: O, Cl, Na, PO_4 (by difference)	....	....	1.1	1.4
Calcium sulphate, $CaSO_4.2H_2O$	....	....	95.8	....
Calcium sulphate, anhydrous	....	....	75.0	93.6

It is very evident that the sand readily dissolves in water. Every rain, no doubt, dissolves some of it and the waters in the district from which the sand was obtained must be heavily charged, probably to the saturation-point, with gypsum. On the evaporation of such water, in the sand or in pools, calcium sulphate is again rapidly deposited.

SAMPLE II. LOCALITY: SAMALAYUCA, CHIHUAHUA, MEXICO.

General Description.—A composite sand, yellowish to light-brown in general appearance. No crystals were detectable in it. The grains were of irregular shape, but of fairly uniform size. None were any larger than the small, uniformly sized ones of Sample I. The grains were angular, with the edges showing the effects of erosion. Glassy and brownish grains predominated. Others with the following colors were to be seen: Amethyst, dull white, dirty yellow, purple, black, and red.

All of this sand passed readily through the sieve used on Sample I. No extraneous matter was found in it.

Qualitative Data.—The sand was very resistant to the solvent action of water, alkalies, and acids, scarcely anything dissolving in these fluids, hot or cold. The colored grains were somewhat reduced in number after treatment with acid, the solution in hydrochloric acid having a yellowish tinge. The sand fused with sodium carbonate with great difficulty. The fused mass was bluish-gray in color. On ignition the sand lost only a slight amount of water. It became pink and yellowish-red in places, but did not fuse, even in platinum over a blowpipe. Carbonic acid gas could not be obtained from it on ignition, so that the sand is obviously entirely

Beach formation on desert island in Guaymas Bay. Mangrove (*Rhizophora*) with its pneumatophores near margin of water, and *Cereus pringlei* within a few feet of it.

Abandoned irrigating ditch near El Riego, Tehuacan. The walls have been built up by lime deposits until the conduit became useless, and it has been cut for a roadway.

Cephalocereus macrocephalus, a tree-cactus near Tehuacan. An epiphyte, a bromeliad, is seen attached to the branches.

Pilocereus fulviceps, a massive tree-cactus near Tehuacan.

free of organic matter. On drying at 110° to 120° C. no change in appearance occurred. This sample contained also minute amounts of calcium, sodium, fluoride sulphate, phosphate, titanite.

Quantitative Analysis.—Preliminary Data.

A. Sand dried in an air-bath at 30° to 35° C.:

(*a*) On drying to constant weight in an air-bath at 50° to 60° C. the quantity of water eliminated was 0.11 per cent.

(*b*) On drying to constant weight in an air-bath at 110° to 120° C. the quantity of water eliminated was 0.19 per cent.

B. Sand dried in an air-bath at 110° to 120° C.:

(*a*) On ignition in platinum over a blowpipe the quantity of water eliminated was 0.5 per cent.

(*b*) On treatment for 3 hours with about 100 parts of hot acids, hot water or cold water per unit of substance the following data were obtained:

.	Solvent.	Substance dissolved.	Residue.
		P. ct.	*P. ct.*
1	One part HCl and three parts H_2O	3.0	97.0
2	Two parts HNO_3 two parts H_2O	2.6	97.4
3	Boiling H_2O	0.5	99.5
4	Cold H_2O (15° C.)	0.6	99.4

(*c*) In a percolation experiment similar to those on Sample I, only 0.4 per cent of the substance dissolved, 99.6 per cent remaining as residue.

Percentage Composition. (Sand dried at 110° to 120° C.)

	I.	II.	Average.
	P. ct.	*P. ct.*	*P. ct.*
SiO	85.9	86.1	86.0
Al_2O_3 Fe_2O_3	8.1	8.3	8.2
Water	0.6	0.4	0.5
O in silicate, plus traces, Ca, Fl, SO_4, etc.	....	....	5.3
Silica and insoluble silicate, not less than	....	....	95.0

General Conclusions.—This sand consists chiefly of silica and of insoluble silicates of iron and aluminum. The results of the extraction experiments, in which relatively large amounts of acid, alkali, and water affected it very little, show that the sand is one of the most insoluble and resistant varieties, and that it is not rapidly altered by weathering influences.

Comparative Composition, Samples I and II.

Direct comparison of results for composition of the two sands is made in the appended summary of average analytic data for substance dried to constant weight at 110° to 120° C.:

(Sand dried at 110° to 120° C.)

	Sample I.	Sample II.
	P. ct.	*P. ct.*
CaO	38.5	trace
SO_3	55.1	trace
SiO_2	3.4	86.0
Al_2O_3 / Fe_2O_3	0.5	8.2
H_2O	1.1	0.5
O in silicate and traces of other elements (by difference)	1.4	5.3
Chief constituents: Calcium sulphate	93.6	....
Silica and silicates	3.9+	94.2+

Sample I, from Tularosa Desert, consists mainly of gypsum.
Sample II, from Samalayuca, is almost entirely silicious.

NOGALES AND THE INTERNATIONAL BOUNDARY REGION.

The region immediately accessible from Nogales and to the westward along the international boundary comprises a series of valleys at altitudes between 3,000 and 4,000 feet, separated by ranges of mountains with a general trend of north and south.

The arid slopes are in the main characterized by yucca-like plants, including *Yucca*, *Nolina*, and *Dasylirion*, while agaves are also in evidence. Two species of oak are abundant. Arboreous opuntias are numerous, and a few species of *Echinocactus* and *Echinocereus* are found. One of the characteristic plants of this region is *Cactus heyderi*, the flattened globose body of which sets so deeply that its upper surface is flush with that of the ground. Spinose shrubs are a prominent feature, but along the streamways *Sambucus mexicana*, *Juglans*, and *Platanus* are fairly abundant. Much detailed work upon the natural history of the region has been accomplished by the members of the various boundary surveys. (See E. A. Mearns, Mammals of the Mexican Boundary Survey, U. S. National Museum Bulletin No. 56, 1907.)

The dome-shaped hills have very steep slopes, which permit the rapid descent of precipitated water, with the result that the streamways often show currents of great volume which last for a few hours only, the channel then becoming dry for long periods, perhaps for months (plate 7). The main mountain ridges offer some fine examples of long

alluvial slopes, which at the northern end of the Sierritas extend for 7 or 8 miles from the more abrupt rocky slopes (plate 7).

TORRES.

The plain in which lies the railroad station Torres has an elevation of about 800 feet above the sea. Its most characteristic vegetation is a growth of small leguminous trees, notably palo fierro (*Olneya tesota*) and palo verde (*Parkinsonia*), two species of *Cereus* of large dimensions (*C. thurberi* and *C. schottii*) (plate 8), and two cylindrical-stemmed species of *Opuntia*. The palo fierro, meaning iron-wood, produces a very hard wood, which, with the lighter but still hard mesquite (*Prosopis*) and the zygophyllaceous guaiacan, or lignum-vitæ (*Guaiacum coulteri*), constitutes the greater part of the fuel used on the railroad locomotives. Palo fierro is considered by the railroad officials a better fuel, by about 25 per cent, than mesquite, and guaiacan about 10 per cent better than palo fierro (plate 9). A metric cord (that is, a pile 3 meters long by 1 meter high and 0.75 meter in length of stick) of mixed palo fierro and guaiacan was considered by an engineer of experience as the equivalent, for fuel, of a ton and a half of the ordinary soft coal available in the Southwest. The palo verde, of which the region contains two species and perhaps more, is an especially abundant tree. It is in use everywhere for household fuel, and one of the species (*Parkinsonia microphylla*) is commonly employed as green forage for horses in winter, the branches being cut and thrown into the corrals, where the horses eat the twigs to the diameter of nearly half an inch. It is probable that at this season the twigs contain a large amount of stored food. *Cereus schottii*, as well as another smaller species of the same genus, is known as sina. *Cereus thurberi* is called pitahaya. One of the common species of *Opuntia*, probably *O. thurberi*, known as siviri, forms a small tree 8 to 15 feet high, with cylindrical joints about half an inch in diameter. It possesses a sour fruit which during the season of drought is an important source of refreshment to wild animals and even to man. The other common cylindrical-stemmed *Opuntia*, called cholla, has joints several times thicker and grows only 2 or 3 feet high, but forms large patches which are a conspicuous feature of the vegetation. Other woody plants showing adaptations to desert conditions are sangre de drago (*Jatropha*), a shrub with whip-like, at this season wholly leafless, brown stems, from which the Papago Indians make some of their baskets; vinorama, a tree acacia (*A. farnesiana*) with yellow scented flowers; papachi, a small rubiaceous tree (*Randia thurberi*) with fruit resembling in appearance a small green orange; bebelama, an unidentified tree with a trunk sometimes 18 inches in diameter, its wood so hard and tough that it is commonly used for wagon fellies; and desota, or tree mimosa, with pink flowers which have the delicious odor of the black locust flower (*Robinia pseudacacia*). This desert produces also

several malpighiaceous and other woody vines which associate themselves with clumps of the trees and shrubs. Among these vines are the saramatraka (*Cereus striata*), with branching stems 0.2 to 0.3 inch in diameter, which reach a length of 4 feet or more, growing through and reclining upon the bushes; and the guarequi (*Ibervillea sonoræ*), a cucurbitaceous tendril-bearing plant whose inordinately thickened root and stem base lies gray and half exposed upon the ground beneath some trellising shrub (plate 10). These tuberous formations may be seen during the dry season lying about wholly unanchored, as the slender roots dry up with the close of the vegetative season, which lasts but a few weeks. In February, 1902, some of these tubers were taken to the New York Botanical Garden, and a large specimen not treated in any way was placed in a museum case, where it has since remained. Annually, at a time fairly coincident with the natural vegetative season in its native habitat, the major vegetative points awaken and send up a few thin shoots which reach a length of about 2 feet only, since they do not obtain sunlight. After a period of a few weeks they die down again and the material in them retreats to the tuber, to await another season. Seven periods of activity have thus been displayed by this specimen with no apparent change in its structure or size. It does not seem unreasonable to suppose, therefore, that the guarequi is a storage structure of such great efficiency that water and other material sufficient to meet the needs of the plant for a quarter of a century are held in reserve in its reservoirs.

The guarequi is reputed locally to be very poisonous, but repeated tests by Dr. William J. Gies and Miss Julia Emerson, with living material, hot and cold water extracts, and alcoholic extracts fail to produce any results with the various animals used as test objects. It is quite possible, however, that the living vines or the fruits might yield substances upon which the prevailing opinion is based.

Westward from Torres the vegetation of the desert continues with little change until the line of hills is approached beyond which the country drops down to a plain still lower and nearer the waters of the Gulf. Here are the tree ocotillo (*Fouquieria*), a brasil (*Hæmatoxylon*), torote prieto (*Terebinthus*), the tree morning-glory (*Ipomœa arborescens*), and the beautiful palo lisso (*Acacia willardiana*). This last is a small tree with the whitest of bark peeling off in tissue-paper films, a slender trunk with graceful spreading branches, and curious compound leaves made up mostly of flat green rachis with an extremely small leaflet area toward the summit. The morning-glory is a tree 20 to 30 feet high, with smooth chalky gray trunk and branches, leafless at this season throughout, its large white flowers opening one by one on the ends of the naked branches. From its white bark the tree is sometimes known as palo blanco, and from the gum or resin which exudes from incisions made in it for the purpose and which is used as incense in religious ceremonies it is called also palo santo.

Pilocereus chrysantha, a small, much-branched tree-cactus near Tehuacan.

Echinocactus grande, Tehuacan. A plant of great age and of maximum size.

Echinocactus flavescens, Tehuacan.

Beaucarnea œdipus, near El Riego, Tehuacan. An inflorescence is seen on the right.

Group of desert vegetation on limestone slopes near El Riego, Tehuacan. *Hectia*, *Agave*, *Yucca*, *Euphorbia*, *Opuntia*, and a leguminous tree are to be seen.

Two trees pass under the name torote blanco; one is a *Terebinthus* with papery buff-colored exfoliating bark; the other is a tree of very similar appearance, but leafless in the winter season and suggestive of *Jatropha* (plate 11).

It was among these desert hills west of Torres that an opportunity was offered to see a Papago Indian extract from a bisnaga (*Echinocactus emoryi*), or barrel cactus, water with which to quench his thirst. He cut the top from a plant about 5 feet high and with a blunt stake of palo verde pounded to a pulp the upper 6 or 8 inches of white flesh in the standing trunk. From this, handful by handful, he squeezed the water into the bowl he had made in the top of the trunk, throwing the discarded pulp on the ground. By this process he secured 2 or 3 quarts of clear liquid, slightly salty and slightly bitter to the taste, but of far better quality than some of the water a desert traveler is occasionally compelled to use. The Papago, dipping this water up in his hands, drank it with evident pleasure, and said that his people were accustomed not only to secure their drinking water in this way in times of extreme drought, but that they used it also to mix their meal preparatory to cooking it into bread.

GUAYMAS.

The flora in the harbor of Guaymas is of a xerophytic character similar to that at Torres, but apparently subjected to severer conditions of aridity. The creosote-bush (*Covillea tridentata*), the plant most widely distributed in the more severely dry deserts of the southwestern United States, appears here again after a long intermission across the plains of northern and middle Sonora. Many of the trees and shrubs are of the same species as those found in the vicinity of Torres, but are of smaller growth.

The hecho (*Cereus pecten-aboriginum*), whose bur-like fruits are used for hair-brushes by the Indians, had appeared along the railroad near the station of Escalante south of Torres, but at Guaymas it was replaced by a species of similar habit, with different fruit, *Cereus pringlei*. A remarkable mixture of plants occurred along the beach in the salt waters of the harbor where small mangroves (*Avicennia* and *Rhizophora*), which we are accustomed to associate with the humid tropics, grew side by side with *Cereus thurberi*, *C. pringlei*, and other characteristic desert plants (plates 12 and 13).

TEHUACAN.

In 1906 a visit was made to southern Mexico for the purpose of making some observations upon the species with storage organs which were known to be abundant in that region, and also to get living material of these plants and of the cacti for experimentation.

It was found convenient to make Tehuacan one of the bases of work. The name of this city is used to characterize an arid region consisting of a series of valleys and plains lying between abrupt limestone hills at an elevation of 4,000 to 5,400 feet, in latitudes 16° to 18°, on the eastern side of the continental divide, the drainage being through the Rio Salado, Rio Quitopec, and Rio Papaloapan into the Gulf of Mexico.

The great valley in which Tehuacan is situated slopes to the eastern margin, where, lying against the base of the mountain, is the streamway of the Rio Salado, the waters of which are wholly used for irrigation. Throughout this valley springs occur on the upper terraces, which in many cases have sufficient volume to be of great service in irrigation. The water appears to be collected under or behind a tilted stratum of clay, and in many places where it does not break through, as in the springs, it is conducted to the surface by tunnels. So far as limited opportunities permitted examination, the construction of these tunnels was begun by digging a well or shaft at the lowest point on the slope or terrace below which water might be expected. If a supply was not obtained by the first, a second was sunk 100 to 200 feet up the slope, and this was continued until water in plenty was obtained. The wells were then joined by sections of tunnel at a level which would allow the water to flow toward the surface lower down, and when it emerged it was run in acequias of the ordinary type.

Most of the shafts examined were from 20 to 40 feet in extreme depth. The excavations were all made by hand labor, the rock and dirt being brought to the surface by means of baskets and vessels, drawn up by a rope of ixtle, the only mechanical aid seen being a single forked branch planted in the ground at one side of the shaft or perhaps two on opposite sides with a cross-bar between.

The accompanying analysis, furnished by Señor Mont of the El Riego Hot Springs, shows that the waters are highly charged with sodium, calcium, and magnesium, besides small proportions of a number of other substances:

Iodine	0.000004	Carbonic acid	0.247872
Sodium	0.204575	Sulphuric acid	0.059244
Potassium	0.015038	Nitric acid	0.009154
Lithium	0.000902	Phosphoric acid	0.000041
Ammonium oxide	0.000952	Arsenious acid	0.000051
Calcium	0.179440	Chlorine	0.131602
Strontium	0.000556	Bromine	0.000187
Barium	0.000081	Boracic acid	0.001920
Magnesium	0.064832	Silicic acid	0.052925
Ferric oxide	0.000255	Residue	0.000009
Manganese dioxide	0.000014		
		Total	0.969654

When the waters of these springs are conducted through the irrigation channels the lime and magnesia are deposited in great quantity on the floor and walls of the ditches. These are constantly built up higher by the use of more soil, which in turn becomes highly charged with lime, and the ditches soon become raised much above the fields. In some cases they reach a level with the source of supply, and a new ditch is started nearby and parallel to the older one (plate 14).

Even with care in the use of water, the soil soon becomes so heavily limed that its usefulness is soon destroyed, and extensive areas were seen upon which cultivation was no longer attempted. The information was also gained that, in some places in the neighborhood of the springs where small intensive gardens were kept, the necessary free and constant use of the water charged the soil so quickly that in about three years it was necessary to remove the surface layer and fill in with top-soil brought from the mountain valleys in which the only irrigation was by surface water of precipitation. Supplies of soil were being brought to the Hacienda El Riego for this purpose during the visit to that place.

So far as general information may be relied upon, the rainfall of this region comes in mid and late summer and can not exceed 15 inches, if the character of the vegetation may be taken as index, although the following record transmitted by the U. S. Weather Bureau shows that Puebla, 70 miles to the northwestward, at an elevation of 7,091 feet, 1,683 feet above Tehuacan, has an annual average precipitation of 36.34 inches.

Months.	Average precipitation, 12 years.	Average temperature, 8 years.	Months.	Average precipitation. 12 years.	Average temperature, 8 years.
January........	0.20	53.4	July...........	5.71	63.3
February.......	0.35	55.8	August.........	7.16	62.8
March.........	0.32	60.8	September.....	6.22	62.1
April..........	1.26	65.0	October........	2.91	60.8
May...........	3.31	65.0	November......	1.06	57.6
June...........	7.56	64.6	December......	0.28	54.3
			Annual......	36.34	60.4

The difference in question might very well be due to the difference in altitude and to the topographical features involved.

Among the agricultural products may be mentioned chilies, maize, the fruits of prickly-pears of various kinds, and sugar-cane. With the combination of desert conditions and the composition of the water, it might be expected that this region would offer some adaptations and features of distribution not encountered elsewhere. Cactaceæ and Liliaceæ

furnish the more highly specialized structures, while the Leguminosæ contribute the greater number of the woody trees and shrubs.

One of the striking features of this region is the extreme localization, or strictness of colonization, exhibited by many species which are found to cover an area of a few square yards, the face of a slope, the crest of a cliff, or the floor of a barranca, with no outliers and with the nearest colony perhaps many miles away.

The Cactaceæ are more abundant here than in any other part of the world yet visited, several of the species being massive forms, which constitute very prominent features of the landscape.

Cereus geometrizans has a short stem with branches reaching a height as great as 15 feet, and is to be found in great abundance in the valleys and canyons that come down into the valley from the west. *Cephalocereus macrocephalus* (plate 15) is a tall species of the massiveness of the sahuaro and like it having a central shaft bearing numbers of branches which are more closely appressed. It was seen only along the cliff near the Rancho San Diego, along the eastern edge of the valley. *Pilocereus fulviceps* (plate 16), of more general distribution on slopes, has a series of branches, in many instances 40 or 50 in number, densely clustered and arising from a short trunk, which barely rises from the ground before it branches. *P. chrysocantha* (plate 17) has more slender branches and frequents the slopes to the northward. Opuntias were much in evidence as inclosures for small plots around dwellings, embracing several varieties and furnishing an edible fruit. *Echinocactus* was represented by a half dozen species, of which one, *E. grande* (plate 17), is undoubtedly the most massive of all the genus, being as much as 8 or 9 feet in height and 30 or even 36 inches in thickness, which, with the many convolutions of its surface, makes it a very grotesque feature of the scenery. The young of this species are characterized by very striking cross-stripes which disappear with age. Upon testing the pith to compare the watery content with the northern species, it was found that so much calcium had been taken up and stored in the form of calcium oxalate or carbonate that the tissue was unpleasantly gritty when chewed, and that its crispness made it difficult to express the juice. *E. flavescens* (plate 18) forms small heads in clusters, while in *E. robusta* colonies 10 or 15 feet across, making mounds 2 or 3 feet high, include hundreds of heads.

No systematic account of any desert is to be found in which the storage function appears so highly developed and by so many species. Of course all of the cacti exhibit this feature in a very marked degree, and a single plant of *Pilocereus fulviceps* may retain several hundred gallons of water. The large stems of *Yucca*, which is a prominent member of the flora of the slopes, function to this purpose to some extent, while the fleshy leaves of *Agave marmorata* and other species, and of *Hectia*, are essentially storage organs for reserve food and surplus water. Here is

Cereus weberi, Tomellin, Mexico.

Plate 22

A forest of *Pilocereus tetetzo*, on mountain slope south of Tomellin, Mexico.

Cereus eburneus and *Agave karwinskii* in margin of field of maize, Oaxaca

View of portion of Salt Lake Desert from near Lakeside, Utah; *Artemisia* in foreground.

also a *Euphorbia* and a *Pedilanthus* with thick upright cylindrical stems, in which the storage function is made more effective by the possession of a thick milky juice.

The tree morning-glory (*Ipomœa*) has a soft, thick trunk, into which a knife may be easily thrust to the hilt, the medullary tissues being highly charged with water and containing some reserve food material.

Perhaps of all of the plants which show this capacity, however, *Beaucarnea œdipus* (plate 19) is the most remarkable. This relative of the *Yucca*, like all plants of this group with narrow leaves, is known as "sotol" and has the bases of the trunks swollen in adult specimens to a diameter of 7 or 8 feet, the topmost branch not reaching a height of more than 25. This trunk has a truncate base resting almost upon the top of the ground, to which it is attached by a few slender roots. This storage organ is composed of a mass of parenchymatous tissue through which run irregularly strands of fibrovascular bundles. After death the loss of water reduces the weight of the storage organ so much that a large plant may be easily toppled over as it stands.

From experimental cultures under way at the Desert Laboratory, the roots appear to have their origin in some deeply internal layer and to push their way forcibly through the thick mass of the storage tissue until the soil is reached. The peculiar form of the stem is predicated by its development in the first three months of the growth of the seedling. The sap has a very bitter taste and it could not be found that any animal makes use of it, no matter how badly in need of water.

Two species of grape were found (*Cissus*) in which enlargements of the climbing stems occurred at the bases or at various heights from the ground, making globoid tubers as much as 5 or 6 inches in diameter, which served as efficient storage and propagative organs. The storage function in this plant is taken on very early in the history of the sporophyte, as was found by the cultivation of seedlings in the Desert Laboratory. In these experiments the hypocotyl and the first internode of the stem were seen to undergo a thickening even when the plantlet bore but one or two leaves and the resulting tuber eventually reached a thickness of 1 to 2 inches.

No reliable records are at hand, but if the character of the vegetation may be relied upon it may be assumed that the precipitation of the Tehuacan region comes within a brief period during the year, during which time a reserve supply may be stored up by plants. By reference to the data given for Puebla, it is to be seen that five-sixths of the rainfall occurs within five months, and five-sevenths within four months, at Puebla, and the general aspect of the vegetation of Tehuacan indicates a shorter rainy season.

The epiphytic habit was prominently displayed by a number of species, including the opuntias and bromeliads. Prickly-pears were seen growing

ınd stone walls, and high up among the bricks and stones of als and other tall buildings. Various species of *Tillandsia* were ..dant on *Fouquieria* sp., shrubs, opuntias, and yuccas. A form ı broader leaves formed striking tufts on the stems of *Cephalo-eus*, to which it simply clung, and no evidence could be obtained of rasitism. One group was seen in which an opuntia had found lodg-ıt in the sinus of a trunk of a *Yucca valida*, forming several internodes, king a stem a yard in length, to which there was clinging tufts of a orm *Tillandsia*.

ile making an examination of these numerous examples of the ge function, which appear to be more numerous here than elsewhere, can not escape the suggestion that possibly the high lime content of soil m facilitate

acan ı o proportion of spinose shrubs, ri quieria ., ı he cacti very few with markedly ıcea ıear surfaces such as ex y *Parkinsonia*, *Parosela*, *Cassia*, *rosopis*, and other leguminous sh plate 20). Of these the sweet quite, *Prosopis dulce*, has a pod ch considerable sweetish tissue rounds the hard seeds. Loran : common and fasten to several cies, including the harder shrubs as ll as the soft *Ipomæa*. So far could be learned during the brief examination, no species were espe-ally protected by poisonous substances except *Rhus potentillæfolia*, which rows on western slopes among other hrubs, looking most unlike a poison ivy. Not being acquainted with its properties, it was handled carelessly, with the result that its dermatitic effects were found to be severe and lasting.

TOMELLIN.

One day was spent in a portion of the same drainage system with Tehuacan at Tomellin, at an elevation of 1,200 feet, which in latitude 19° N. gives distinctly tropical conditions. Here is perhaps the most massive of all cacti, *Cereus weberi* (plate 21), which with its numerous thick branches arising from a central stem within a short distance from the ground, is found on the hill slopes and valleys. Near it was the much-branched slender *Escontria chiotilla*, while an *Echinocactus* and a few species of *Opuntia* are found in among the woody shrubs. Leguminous trees and shrubs come in to form a greater part of the landscape, showing a distinctly tropical influence, and some trees of *Juliana* of the newly erected family of Julianaceæ were found near the station. A short distance to the southward *Pilocereus tetetzo* formed great forests on the slopes facing the afternoon sun (plate 22).

OAXACA AND MITLA.

The city of Oaxaca de Juarez lies on an elevated plain at an elevation of 5,067 feet, the adjacent areas being in the drainage which eventually reaches the Pacific by the Rio Tehuantepec and the Rio Verde. Although near some mountains of considerable altitude, the precipitation is comparatively small, as may be seen from the following transcript furnished by the U. S. Weather Bureau, which shows the average precipitation at Oaxaca for a period of ten years:

January	0.12	July	4.09
February	0.55	August	4.25
March	0.59	September	5.94
April	1.77	October	2.91
May	3.94	November	0.39
June	8.62	December	0.04
		Annual	33.21

As one proceeds to the ancient ruins of Mitla, 36 miles to the southeastward, the aridity increases until in the vicinity of the hacienda of that name extreme desert conditions are found. The ancient structures here are indicative of a type of civilization characteristic of the desert, in which coöperation or communism was carried to as great lengths as it must have been in the pueblos of the northern deserts in America.

A short distance to the eastward from Oaxaca lies the village of El Tule, in which grow a large number of cypress trees (*Taxodium mucronatum*), one of which stands in the churchyard, and by the claims of local patriotism is the greatest in the world, while for a long time it has been cited as the oldest living. Both of these claims are incapable of actual proof, although the tree has much to justify an interest in it. Six feet from the ground it measures 154 feet in circumference, but it may be really two or three individuals fused together, as it divides into that many main branches within 50 feet. This tree has been an object of observation for more than two centuries, and on one side is a tablet, partly covered by the growth of the outer layers of the trunk, signed by the great naturalist, Baron von Humboldt, and probably placed there by his direction a century ago.

From El Tule to Mitla the way passes between fields illustrating methods of agriculture in an arid tropical climate. Not the least interesting of these features are the crops of maize of species either primitive or directly derived from one of the elementary species of *Zea*. The highway, especially where it passes through small villages or near a hacienda, is marked off from the fields and compounds by barriers of cacti grown in dense rows. Two or three species of *Cereus* and several pricklypears are used for this purpose and also yield a valuable crop of fruit for the owners (plate 23).

More than one of the species in both groups assume an arboreal form, while several were encountered which were definitely known to be as yet undescribed.

A great number of woody shrubs of the type known in such arid regions were seen on the hill-slopes, while down near the streamways an ash (*Fraxinus*) assumed well-developed proportions. The plant most reminiscent of the tropics, however, is the *Ficus*, which in favorable situations shows a great spread of branches and makes a large number of roots above the surface of the ground.

In the markets of the villages from Oaxaca to Mitla trimmed root-stocks of a yucca were on sale which are used by the native population for soap, especially in dressing the hair, although it probably is applied otherwise also.

At Mitla were seen a few living specimens of *Nopalea*, a cactus not encountered elsewhere on the trip, while a similarly rare form, *Pereskiopsis chapistle*, was seen in the suburbs of Oaxaca. The latter was in close proximity to a huge shrub, probably a *Boehmeria*, or some other member of the nettle family, which was sedulously avoided by our driver as being capable of inflicting very painful stings.

At Mitla the opportunity was offered for seeing the manufacture of mescal from *Agave*. Plants of several species and horticultural varieties of *Agave*, as well as of *Yucca* and *Dasylirion*, are uprooted at a time when the plant is about to send up its long inflorescence axis and is loaded with sugary substances. The leaves and roots are trimmed away, leaving a huge core in the case of the large agaves. A large pit is heated by means of a hardwood fire built in it, and after being cleansed of ashes and the remains of the fire the cores are piled in the cavity and covered, and allowed to bake slowly for two or three days. Next the pit is uncovered and the cores removed to a large vat made by sewing the edges of three or four cowskins together and suspending them from a framework of rough branches. Fermentation is allowed to act upon the sugary material for a week or ten days, and then the unpleasantly smelling liquid is dipped out and put in the kettle of a rude still, the cap of which is connected with pipes cooled with water run in wooden conduits from a stream or acequia near by. The resulting liquor contains a mixture of several alcohols and is exceedingly fiery, being a true whisky of a desert people.

SAGE-BRUSH DESERTS OF NEVADA AND UTAH.

A large area in Nevada and Utah, lying at elevations up to 5,000 feet, includes numerous valleys and widely extended plains with no outlet for the drainage. Into these the streams from the mountains flow and terminate in lakes at the lowermost part of the natural basin formed, or spread out in great flats or playas in such manner that the waters disappear in the ground, forming what are known as sinks, of which that of

Ants' nest among sage-brush (*Artemisia tridentata*) Elko, Nevada.

Opuntia pusilla, and low spinose shrubs of desert near Hazen, Nevada.

Plate 27

The desert plain of Las Vegas, Nevada, showing expanses of loose alkaline soil.

Plate 28

Clumps of desert vegetation near Las Vegas, Nevada. *Petalomyx nitidens* in foreground.

the Humboldt River is an example. The Great Salt Lake of Utah is an illustration of the survival of a lake in the bottom of the basin. In either case the soil of the basin in many places becomes highly charged with salts, especially in the sinks and in the vicinity of the lakes, which show a decreasing or widely varying volume.

In addition, the precipitation on areas outside of the mountain peaks and slopes is low in comparison with the annual rate of evaporation. This is true also of regions in these two States in the drainage system of the Colorado River, with the result that a highly xerophilous vegetation of great extent is encountered. The predominant forms in this flora consist of perennial compositaceous shrubs, of which the genus *Artemisia* furnishes three or four species. These constitute the most prominent feature of the deserts in question under the local appellations of sage-brush, greasewood, and desert-sage (plate 24).

Such a flora is to be seen to advantage in the vicinity of Great Salt Lake, Utah. To the southwest of this lake lies the area formerly known as the Great American Desert, in which the soil is so highly charged with salts that extensive areas are devoid of any covering of seed-plants (plate 24). The main stretch of this arid area is about 125 miles from north to south and is about 50 miles at its greatest width. It was traversed by one of the main routes of the old emigrant trail to California, and consequently finds prominent mention in the descriptions of travel and surveys of half a century ago. Perhaps no better characterization of the general aspect of the region could be given than by the following citations from Bryant (What I saw in California, 1848, New York). He says:

> From the western terminus of this ominous-looking passage we had a view of the vast desert-plain before us, which, as far as the eye could penetrate, was of a snowy whiteness and resembled a scene of wintry frosts and icy desolation. Not a shrub or object of any kind rose above the surface for the eye to rest upon. * * * Descending the precipitous elevation upon which we stood, we entered upon the smooth, hard plain we had just been surveying with so much doubt and interest, composed of bluish clay, incrusted in wavy lines with a white saline incrustation. * * * * Beyond this we crossed what appeared to have been the beds of several small lakes, the waters of which have evaporated, thickly incrusted with salt and separated from each other by small mound-shaped elevations of white, sandy or ashy earth, so imponderous that it has been driven by the action of the winds into these heaps, which are constantly changing their positions and their shapes. Our mules waded through these ashy undulations, sometimes sinking to their knees and at other times to their bellies, creating a dust that rose above and hung over us like a dense fog.

At elevations of about 4,000 feet the soil, which is subject to the leaching action of natural drainage, bears the sage-brush, *Artemisia tridentata* (plate 25), as the predominant form, both as to general landscape effect and actual population, over many thousands of square miles, in which but little else besides low annuals occur. Succulents are rare and comprise not more than two or three species of cacti.

At levels slightly lower than the above, such as a locality examined near Hazen, Nevada, many other small shrubs and annuals gain in number, such as *Sarcobatus vermiculatus*, *Artemisia spinosa*, *Chrysothamnus*, *Thamnus montana*, *Tetradymia glabrata*, and *Lycium andersonii*. An *Ephedra* is also prominent, while *Lepidium fremontii* is abundant in many places. With these is also to befound *Opuntia pusilla*, which forms small mounds or tufts of dead branches and gathers débris blown by the wind, from which the living stems barely emerge (plate 26). One or perhaps two species of prickly-pear are also encountered.

The absence of succulents and of plants with storage structures is quite noticeable at elevations above 3,000 feet and in the northern part of the region under discussion, although the conditions of precipitation would render such capacity highly advantageous. The low winter and night temperatures, however, probably render such structures impossible because of the liability to freezing. As one descends the valleys and canyons leading to the drainage of the Colorado River in southern Nevada quite a variety of such forms are encountered, among which are numerous opuntias and a large *Echinocactus*, with the tree *Yucca* coming in still lower down.

A characteristic area is that around Las Vegas, Nevada, a bolson of great extent (plates 27 and 28), the surface of which includes great spaces covered with a loose alkaline soil which is hardened to a thin, fragile crust on the surface, while there also occur soft, slippery patches of moist alkali bearing *Allenrolfea*. Small arrested dunes bearing low mesquite shrubs are numerous, but in no place were free, moving dunes encountered. In general the vegetation consists chiefly of spinose types, or of forms either with heavily coated leaves or with very restricted blades (plate 28). The geological studies of the great basins of this region lead to well-founded conclusions as to major oscillations in climate in which long periods of aridity and humidity have alternated. It is concluded that one climax of aridity was reached about three centuries ago and that the precipitation is now slowly increasing, at a rate not appreciable by direct methods of measurement, however. (See page 104.)

THE MOHAVE DESERT.

Ascending from the San Bernardino Valley northward through the long climb of Cajon Pass, the railroad at last emerges from the dense growth of chaparral and comes out upon the elevated plain of the Mohave Desert. About 4 miles north of the summit begin to occur small groves of the strange tree for which the western part of the Mohave Desert is most widely known, the tree-yucca (*Yucca arborescens*). Within a few miles the desert becomes almost a forest of yucca and juniper (*Juniperus californica*), the former reaching a height, ordinarily, of 12 to 15 feet, though occasionally exceeding 25 feet and attaining a diameter of nearly

2 feet. At the station Hesperia the juniper ends and the creosote-bush (*Covillea tridentata*) begins. As still lower elevations are reached, the creosote-bush becomes, except in the washes, the prevailing bush, and continues throughout the long waste of desert to the Colorado River. (See F. V. Coville, Botany of the Death Valley Expedition, Cont. U. S. Nat. Herb., 4, 1893, for a fuller account of the vegetation.)

DEATH VALLEY.

In 1891 Mr. Frederick V. Coville made a botanical examination of the Mohave Desert and of the Death Valley regions in southern California. The work was designed to be both systematic and comprehensive. It embraced a delineation of the principal vegetative conditions to be met with in deserts, some investigations of the relations of the chief environmental factors to the characteristic plants, and an examination of the more important adaptations of a large number of species. One of the features of this contribution of great importance was the recognition of the major problems to be encountered and an outline of further researches needed upon the subject. The region included in this survey consists, in large part, of mesas in which *Covillea* and *Gaertneria* are the prevailing plants. The surface layers of the soil consist of gravel, sand, and boulders. An average of the data obtained by the ten Weather Bureau stations nearest the region showed a rainfall of about 5 inches annually, and a precipitation amounting to 1.54 inches was observed in the region itself from January to June, inclusive, in 1891. The extreme dryness of the atmosphere is illustrated by the fact that the relative humidity at 5 p.m., taken daily during the five months mentioned, was 15.6 per cent. On the 4th and 5th of August of the same season a minimum of 5 per cent was recorded. A maximum temperature of 122° F. was recorded five times during the summer season of 1891 and a minimum of 30° was reached in January and February of the same year. Vegetation in this district was seen to exhibit its greatest activity during the period of maximum precipitation, with medium temperatures from February to May; a quiescent condition during the season of maximum temperature and dryness during June to November; and a condition of slow growth during the low temperatures of December and January.

Perhaps the most noteworthy result of this study of the flora consisted in the discovery that the vegetation was composed almost wholly of perennial shrubs and annual herbs, and but few structures for storage of water were found. The tendency to form fleshy fruits was almost lacking, and even the fruits of *Opuntia* were comparatively dry and hard. The root-systems of a number of plants were examined and the mesquite (*Prosopis*) was found to have roots more than 50 feet long. Growth or increase in length and thickness was found to be extremely slow in the perennials, though very rapid in the annuals which carry out their entire

vegetative and reproductive cycle during the period of maximum precipitation. Many interesting facts are also cited as to the uses of hairy coverings and resinous coating in the prevention of damage by extreme evaporation of water and intense radiation.

GRAND CANYON OF THE COLORADO RIVER.

The Colorado River comes down into the great Nevadan-Sonoran Desert through the deep canyon in northern Arizona, from which it emerges to be directly bordered on either hand by pronounced arid areas at low altitudes. An examination was therefore made to ascertain to what extent the xerophilous plants of the lower deserts had extended up along the shelves and terraces of the canyon at the elevation of the open deserts. Three visits in all were made to the canyon, one solely for the purpose of getting an impression of the range of vegetation from the timbered rim at 6,866 feet at the end of the railway leading to it, down the Bright Angel trail to the river at 2,436 feet.

For the first 2,600 feet of the descent the trees continue, but from that point to the river the slopes are treeless and the vegetation of a desert character. A very striking feature is extensive fields of a rosaceous shrub, *Coleogyne ramosissima*, which extends in an almost pure growth over the canyon terrace at an elevation of about 3,600 feet in a soil seemingly well supplied with lime (plate 29). There is a notable absence of many shrubs which would be present in the open desert at the elevation afforded by the lower parts of the canyon, and which have a seemingly good route for extension up the canyon from the Mohave Desert. The absence of these plants is presumably connected with the narrowness of the canyon, which, besides producing abnormal air-currents and temperature conditions, is responsible for a rainfall greater than would occur at the same elevations in the open desert. A cloud sheet precipitating rain on the 7,000-foot plateau through which the canyon passes would presumably continue to condense as it drifted across the canyon, whereas if it should drift off the plateau over a desert of low elevation its precipitation would be greatly lessened or would cease altogether.

Furthermore, the canyon exerts some influence upon the conditions affecting vegetation on its rim. The heated air from the lower warmer levels rises, expanding as it does so and increasing its relative humidity, with the result that during the daytime a current of air, cooler and moister than the air on the mesa, pours out of the canyon over its rim. The effect of this is strikingly illustrated in the region of the Coconino Forest, where many species not seen elsewhere on the mesa are to be found fringing the rim of the canyon. *Razoumofskya vaginata* (Willd.) Kuntze is a loranthaceous parasite growing on the branches of the bull pine (*Pinus scopulorum*) throughout the transition zone. It is most abundant, however, along the margins of mesas, the rims of canyons, and certain hilltops.

Plate 29

Along the Bright Angel trail, Grand Canyon of the Colorado, Arizona. The prevailing plant is a rosaceous shrub (*Coleogyne ramosissima*). (Reprinted from Publication No. 6.)

Delta of Colorado River in flood as seen from Cucopa Mountains. The main channel is that of the Hardy. Islands of vegetation visible above the water. April, 1905.

Newly made land in the delta of the Colorado River, on which *Atriplex* and *Prosopis* have become established.

Plate 32

Colorado River and margin of Sonoran desert near international boundary. Groves of *Populus* and *Salix* in the alluvial land to right and center. Gravel mesa with *Covillea* and *Ephedra* to left.

It reaches its greatest abundance along the Grand Canyon of the Colorado River. Here the heated air, rising from the river-bed under the influence of a subtropical sun, loses about 20° F. in its ascent of about a mile, and as a consequence it pours over the mesa much cooler and with its relative humidity increased to near the point of saturation. The *Razoumofskya* finds the strip of territory where the full effect of the moist current is greatest most advantageous in the germination of its seeds and the attachment of the seedlings to the host plant. It is therefore most abundant in a belt 1 or 2 miles in width running parallel to the rim of the canyon, while it is comparatively infrequent at greater distances. Within this belt it is estimated to have gained a foothold on 60 to 80 per cent of the pines.

THE DELTA OF THE COLORADO RIVER.

The action of the Colorado River in its delta, in its occasional overflows of the Salton and Pattie basins, and the interwoven conditions affecting the origin and development of the floras of the delta and contiguous deserts, are such that the principal features of the delta must be considered.

The main portion of this delta consists of an alluvial plain a few feet above low-water mark, cut in all directions by sloughs and bayous, which are filled at irregular intervals, but principally by the annual floods of May, June, and July, resulting from melting snows in the headwater region of the river. Occasionally, however, midwinter floods occur, due to rain and melting snow in the region drained by the Little Colorado, the Bill Williams River, and the Gila (plate 30).

In contrast with the desert the delta is characterized by almost pure cultures of various plants in different areas. Thus in places seedling willows and poplars occupy areas of great extent to the almost total exclusion of all other seed plants. The cat-tail tule (*Typha angustifolia*) lines the shore of the river for many miles and extends back from it so densely that, except an occasional mesquite or screw-bean, nothing else may compete with it. In other places the arrow-weed (*Pluchea sericea*), quelite (*Amarantus palmeri*), wild hemp (*Sesbania macrocarpa*), salt-grass (*Distichlis spicata*), *Cressa*, and wild rice (*Uniola palmeri*) occur in similar density. Filling in the interstices, as it were, between the larger blocks occupied by these colonies are the mesquite and screw-bean (*Prosopis velutinea* and *P. pubescens*), cane or carrizo (*Phragmites phragmites*), *Scirpus fluviatilis*, and *S. californicus*, the two sedges of the delta, cow-pumpkin (*Cucurbita palmata*), *Lippia cuneifolia*, *Eclipta alba*, *Echinochloa crus-galli*, *Diplachne imbricata*, and dock (*Rumex*).

The tidal action of the waters of the Gulf of California is felt as far up the river as Colonia Lerdo, 75 miles from the mouth, and shortly below the limit of such action the trees begin to find the soil too highly charged with sea-salts, and great flats occur in which an occasional mesquite and salt bushes (*Atriplex*) find a foothold. Within the memory

of men now living the trees have moved southward toward the Gulf a distance of 8 or 10 miles, indicative of the extension of the delta conditions by accretions to the deposits around the mouth of the river (plate 31).

The river cuts directly into the gravelly plain or mesa of the Sonoran Desert at four points on the eastern margin of the delta (plate 32). At these places may be found within a compass of 100 feet the most vivid contrasts of rank swamp vegetation and water-loving plants having broad leaves and delicate tissues with the toughened, spinose and hairy xerophytic forms of the desert. The presence of the moist area of the delta has but little effect upon the climate of contiguous arid regions, although a popular supposition to the contrary promises fairly to be immortal. The relative humidity here is often as low as 17 per cent within 50 feet of the margin of the water. During the recent visit to this region, however, clouds of mosquitoes from the delta had been blown for many miles across the sandy plains, and these pestiferous swarms among the creosote and sage bushes gave a deceptive but unalluring appearance of alteration of climatic factors.

A shallow depression extends up from the eastern side of the Gulf of California to the main channel of the Colorado River about the head of tidewater, but its upper end is above the ordinary level of the river. Seepage water gathers in the channel at a point within a few miles of the river and finds its way to the sea, gathering salt from the soil and from the tides that push up into it, the whole being designated as the Santa Clara Slough. Here are found interesting combinations of xerophytic plants on the sand-dunes near the water, and of the halophytes or fleshy, salt-loving plants that border the water and cover the mud-flats adjacent to it. During some explorations in this region in 1905 the flood-waters of the Colorado River were seen to be making their way down through this channel to the Gulf, and a slight cutting action of the current might readily make this the main outlet.

Late in 1907 it was found that the main current of the river was actually making its way to the Gulf through this channel, even at the low-water stage, a change which might have the profoundest influence on all life in several hundred square miles of the delta.

THE SONORAN DESERT.

The region east of the delta of the Colorado River and extending southward along the Gulf of California consists principally of a series of sandy, gravelly plains near the delta and the coast, with moving dunes or "sables" in places, while in some localities these are replaced with mounds a few yards in height bearing *Ephedra*, *Covillea*, and *Prosopis*. (See plate 33.)

In addition to the few herbaceous annuals which arise during the season favorable for growth, the principal types are perennials with spinose branches and reduced deciduous leaves, although a few species

with hardy leaves are included. *Ephedra*, *Gaertneria albicaulis*, *Oenothera claviformis*, *Lupinus mexicanus*, *Abronia villosa*, *Astragalus vaseyi*, *Plantago scariosa*, *Langloisia schottii*, *Stillingia annua*, *Asclepias subulata*, and *Fouquieria splendens* are typical examples, while a few forms with deeply lying bulbs are also found here, including *Hesperocallis undulatus*.

To the eastward are to be found series of mountain ranges, generally of considerable height and including many old volcanic cones, in which the water-supply and the precipitation are extremely scanty. Among the ranges, and in a manner inclosed between them, are gently sloping valleys and great plains with no well-defined drainage, which bear a characteristic shrubby vegetation. In the higher levels are encountered succulents and storage forms of the general character found in the Torres district. Burseras, known as "torote," are abundant, and a copal tree (*Terebinthus macdougali*, plate 40) is found near the Gulf. Accurate information concerning this region is, however, difficult to obtain, and it may be made the object of explorations from the Desert Laboratory. Accounts of some explorations in this region are to be found in Bull. Amer. Geog. Soc. 1907 (plate 34).

THE COLORADO DESERT.

The Colorado Desert, which has been mistakenly supposed by many writers to lie in the State of that name, in reality is situated in the south-eastern part of California. Perhaps no better description of its limits could be made than from the following citation from Prof. W. P. Blake (Explorations and Surveys for a Railroad Route from the Mississippi River to the Pacific Ocean, War Department, 1855, p. 228), who examined this region in 1852, and by his barometric observations first established the fact that it included a basin lying below sea-level.

> The region of country known as the Colorado Desert is a long plain or valley west of the Colorado River, near its mouth. It extends from the base of Mount San Bernardino to the head of the Gulf of California, and is separated from the coast slope by the Peninsula Mountains. The limits of the plain on the north and northeast are determined by the ranges of mountains which extend from San Bernardino Mountain to the mouth of the Gila and beyond into Sonora. On the south and east the desert is bounded by the Colorado River and the Gulf. The area thus bounded is a long and nearly level plain, extending in a northwest and southeast direction from latitude 43° on the north to the parallel of 32° on the south. Its greatest length in this direction, from the base of San Bernardino Pass to the Gulf, is 180 miles, or, measuring from the base of the pass to the mouth of the Gila, it is 140 miles. Its greatest width is about 75 miles, measured in a north-and-south direction along the Colorado River, between the head of the Gulf and the mountains north of Fort Yuma. The plain narrows as it extends back from the Colorado River and opposite Carrizo Creek its width is reduced to between 60 and 70 miles, and still farther westward, near to its extremity at the San Bernardino Pass, it will not average over 25 miles. These measurements are approximate, and give for the whole area west of the Colorado about 8,250 square miles; or, including a portion of the plain beyond the river, about 9,000 square miles.

The desert conditions extend across the Colorado River and southward, including the mesas of western Sonora. To the southward the Colorado Desert proper passes into the Pattie Basin and the low Eastern coastal plain of the Peninsula of California, portions of which are of an extremely arid character.

Chief interest centers in the Salton Basin and the region inclosed by the ancient beach-line, which is 20 to 30 feet above mean tidewater. Slightly above this, on the northern side of the basin, is exposed the edge of a clay stratum in the foothills of the San Bernardino Mountains which serves to bring to the surface all of the water percolating from the gravel above them. Along this ledge is a belt of palms (*Neowashingtonia*) (plate 35), which in some places follows the clay exposure so closely as to make a horizontal line in the landscape, while in other places the seepage collects in the mouths of canyons and below the clay in sufficient volume to support colonies or oases of this beautiful tree (plate 36).

One of the most convenient points from which to visit the native palm groves of the Colorado Desert is the town of Indio. The San Bernardino Mountains, high and timbered in their main western portion, send out eastward for many miles into the desert a low timberless spur. Its parched rocky slopes seem, at the distance of a few miles, to be devoid of any vegetation whatever, but upon closer inspection are found to be sparsely dotted with bushes, like the plains portion of the desert. The canyons of this spur open out upon the valley in broad deltas of gravel brought down by occasional torrents. Just within the mouths of some of the canyons occur groves of a native fan-leaved palm (*Neowashingtonia robusta*).

The ordinary diameter of the trunk is about 2 feet and the trees at full maturity are about 50 feet high. Most of the old trunks are blackened, apparently by fire. The younger trees retain their dead leaves for several years, folded downward over the trunk and forming a cylindrical mass about 8 feet through and sometimes 18 feet in height. As the trees grow taller the lower of these dead leaves fall to the ground, leaving a naked trunk with a head of green leaves at the summit and a collar of dead leaves just underneath.

All the trees seem to stand on the same general level, not far above the base of the range. A close inspection showed that they grew in a moist clay soil, incrusted with alkali. Apparently such rain as falls upon the mountains and sinks into the earth is caught upon this clay table and runs over it to the exposed margin, where for several miles it forms a line of miniature oases containing the palms and various plants characteristic of alkaline springs. These include mesquite bushes (*Prosopis*), salt-grass (*Distichlis spicata*), a rush (*Juncus*), a sedge (*Cyperus*), and an orchid (*Epipactis gigantea*). Within the canyon and upon the delta were found a few desert shrubs not met with earlier, the leguminous

Gravelly desert in Sonora near Colonia Lerdo. The surface is composed of polished pebbles, from among which the sand has been carried by the wind. The scattered vegetation includes *Covillea, Ephedra, Gaertneria*, and a few stunted mesquite shrubs.

Oasis of palms (*Neowashingtonia filifera*, in the mouth of a canyon near Indio, Colorado Desert.

Parosela spinosa and another species of the same genus, and the composite green-leaved *Peucephyllum schottii*.

West of Indio the railroad passes through a strip of mesquite dunes. Most of the sand here lies in hummocks, each produced by a mesquite tree (*Prosopis*), about which, and finally through the branches of which, the sand has drifted until only the ends of the branches project and the hummock presents the appearance of being covered with a growth of brambles.

The total precipitation in this region is probably not more than 3 inches annually, and as this comes uncertainly and irregularly one finds but few forms with pronounced storage organs, although on the mountain slopes several species of *Opuntia* find lodgment, and a barrel-cactus (*Echinocactus cylindraceus*) grows in places where it must depend chiefly upon drainage from the slopes above, which receive a greater amount, or where the total of a large area is collected in underground conduits. It would be difficult to give accurate records of temperature, although as high as 128° F. is reported from certain places in this basin in midsummer. Ice may be formed in the winter, however. The mountains to the west of the Colorado Desert are subject to sudden storms, in which the rainfall is very heavy for short periods. Thus at Campo a precipitation of 16.10 inches was measured within a few hours in one day. The "Sonoras," or storms, which give this precipitation are usually confined to the main mountain ridges in their effects, but occasionally one drifts to the eastward far enough to cast some water upon the Colorado Desert; and in fact most of its total precipitation may come in this manner.

The surface of the basin consists for the most part of loam, which in places is gravelly and in other places very sandy, while elsewhere fragments of rock cover the entire surface, particularly on the western slopes. Almost all of the loam is more or less saline and alkaline, the proportion of salts present being the principal factor determining the character of the vegetation on any area, with the physical characters of secondary importance.

The leached gravelly slopes bear *Covillea* and a variety of woody perennials, among which are to be included *Fouquieria splendens*, *Olneya tesota*, *Ephedra*, and *Parkinsonia torreyana* (plate 37), while along the beds of the dry streamways *Parosela spinosa* is abundant and also the composite bush with bur-like fruits, *Gaertneria dumosa*. The salt-bushes *Atriplex canescens* and *A. polycarpa* inhabit saline areas, the latter showing a wide range of capacity in being able to live not only in slightly saline but highly alkaline soils.

The more highly alkaline areas bear *Allenrolfea* and *Sueda* (plate 38), chiefly, while in such places the small shallow drainage channels, not wider than a hand's breadth and less than an inch in depth, become sufficiently leached to permit the growth of a half dozen small annuals.

On various parts of the sloping walls of the basin are saline and alkaline springs. The flow in most of these springs is very slow, and low mounds are built up around the small pool of water, the soil becoming incrusted with the salts by evaporation. Four plants make up most of the vegetation, salt-grass (*Distichlis spicata*), *Allenrolfea occidentalis*, reed (*Phragmites phragmites*), and a rush (*Juncus cooperi*). This last plant grows in enormous tufts and is of pronounced effectiveness as a soil-builder. In some of the moister springs, with soft, deep black mud, a three-angled spike-rush (*Scirpus olneyi*) was found, and in others the arrow-weed of the desert marshes.

Between Rimlon and Palm Springs is an area in which the vegetation is subjected to strong sand-laden winds, a veritable sand-blast. The western faces of the wooden telegraph poles are deeply cut within 2 feet of the ground by the sharp, driving sand, and the railroad employees have found it necessary to pile stones about the bases of the poles in some spots to keep them from being actually cut off. The creosote-bushes have been molded into the most fantastic shapes. One of them standing in the lee of a small boulder ran its branches freely to the eastward, but the twigs that project upward and outward beyond the protection of the boulder were killed by the sand blast, so that the plant presented the appearance of a miniature box hedge about 1.5 feet high and wide and extending about 4 feet from the rock.

Clumps of *Ephedra* and plants of *Yucca mohavensis*, the cylindrical-stemmed *Opuntia bigelovii* and *O. echinocarpa*, and the flat-stemmed and spineless *O. basilaris* vary the desert vegetation until, in the vicinity of the station Cabezon, the creosote-bush ceases and the white sage (*Ramona polystachya*) and various other plants from the coastward side of the San Bernardino-San Jacinto Mountain barrier come out a little way through San Gorgonio Pass to meet the plants of the desert.

In the western part of the desert the clay forms the floor upon which in some places a thin layer of gravelly soil rests, while in other places the bare clay does not afford a foothold for seed-plants of any kind. Upon the eastern edge of the region lie the great sand-dunes which are known as "Los Algodones," a name of Indian origin. These dunes are the more ordinary rounded hillocks by reason of the varying direction of the wind and are moving in a general northeasterly direction as a resultant. Such dunes actually support a very scant vegetation.

A second series of lesser height, but scattered over a great area, are to be found in the great alluvial fan of the streamway of Carrizo Creek. Here the dunes are of the rarer crescentic form indicative of a steady wind in one direction with but little local deflection, the concave leeward face having a very steep slope and the convex windward slope being very gradual. Similar dunes on the Desert of Islay, in Peru, have recently been described by Prof. Solon Bailey (The Sand Dunes of the Desert of

Islay, Ann. Astronomical Observatory, Harvard College, vol. 39, pt. 2, 1906, p. 287) and are also found in the desert of Seistan, Persia. These dunes are rarely over 15 or 20 feet in height, and a plant in the way of the crest of the dune may be destroyed before it is uncovered by the advancing wave of sand.

Some of the woody plants exhibit many interesting capacities in the way of elongation of the stems with restoring curvatures, by which those encountering the thinner portions of the dune are enabled to survive the inundation even when it is greatly prolonged (plate 39).

The principal trail, still in use across the mountains in southern California, cuts across the southwestern portion of the Salton Basin and up the Carrizo Creek drainage system, passing for many miles through the sand of this region. During periods of high winds and storms the amount of sand carried along is so great as to make travel impossible. During such storms the experienced traveler shelters his animals as securely as he may against the cutting wind, and watches his wagons to prevent any deposit of sand, which might quickly grow into a dune of respectable size and impede his departure from the place after the storm.

The Carrizo slopes bear numerous seepages, or slow springs, and as the sand moves along some of it is wetted when it reaches such a spring and remains in place. To this small moist heap other particles become attached by moisture until a mound of some height may be formed, which affords lodgment for a few perennial shrubs such as the mesquite.

The growth of these bushes serves to bind the sand still further. The seepage may vary, or the wind, in conjunction with the sun, may dry out and move some of the sand, killing the shrubs. As a final result such dunes may be disintegrated, while others, still intact and serving as retreats for numerous desert rats and small rodents, will be encountered nearby (plate 40).

The bottom of the Salton Basin lies 286 feet below sea-level, and an ancient beach-line 20-30 feet above sea-level incloses it, showing unmistakably that the basin at one time was filled with water. Furthermore, an examination of the gravelly slopes reveals great numbers of minor beach-lines, indicative of levels at which the water has stood for extended periods. According to concurrent testimony of geologists, this basin was at one time the head of the Gulf of California and was cut off by the deposition of silt from the river entering it from one side, since which time the occurrence of water in the basin has been irregular. Until recently the flood-waters of the river overflowed the banks of the river and, spreading over the sloping alluvial plain, finally found their way into the basin in some volume, cutting indefinite channels here and there, the most prominent of which were designated as New River and Alamo River. These channels did not begin as definite outlets from the river, and simply ran across the plain for some distance, then widened and terminated. The string

of pools found in their beds long after the flood-waters had subsided were a very important factor in desert travel.

In 1904, however, an irrigation system was instituted to lead the water from the river around onto a vast area of the slope of the basin, which was found to be unusually fertile and which was rapidly occupied with settlers. Canals and openings were connected with the river without proper headworks, with the result that the water rushed in with great cutting power and deepened the channels to such an extent that the entire current of the river was diverted into the basin for several months, inundating 500 square miles of desert and forming a lake, the deepest part of which gave soundings of 84 feet (plate 41).

The fresh water thus poured into the basin took up the salts from the saline and alkaline soils, with the result that when the inflow of the river was checked, February 10, 1907, a total solid content of one-third of one per cent was present.

A detailed analysis of the salts taken up by the fresh water poured into the basin reveals the fact that their total composition resembles that of condensed river-water rather than sea-water. This agrees perfectly with the supposition that since the last waters from the Gulf evaporated in this basin directly after connection had been closed by alluvial deposits the river has poured flood-water into the basin scores, perhaps hundreds, of times, and with it much salt, so that the bottom of the ancient head of the Gulf has been buried beneath a layer of river deposits, and that on top and with this deposit are the salts from the river, which are now redissolved by the present flood.

Preliminary examinations having already been made, the lake was circumnavigated at this time by an expedition from the Desert Laboratory, and localities selected for the observation of the movements of vegetation as the waters receded by evaporation. Among the major phenomena to be critically examined are possible introductions by reason of the inflow of the river-current, and the manner in which the submerged portion of the basin will be reoccupied by the plants that formerly inhabited it. Fortunately the bottom of the basin had been examined in 1903 and a sketch of the vegetation made as it then existed, which will afford some basis for comparison (plate 42).

THE CUCOPA MOUNTAINS AND THE PATTIE BASIN.

To the northward of the Cucopa Mountains lies the depression of the Salton Basin which is subject to flooding; to the eastward is the strait which formerly connected this basin with the Gulf of California, and which is now a part of the delta of the Colorado River. As the water in the various channels makes its way across the delta it comes against the eastern base of the mountains and gathers in the Hardy River, the current of which actually bathes the foot of the rocky slopes in places (plate 34).

Dry streamway in Salton basin. *Parkinsonia torreyana* in center, with smaller trees of *Parosela spinosa* to right and left.

Plate 38

Saline deposits in lower part of Salton basin, 1903. The principal plant is *Allenrolfea*. This area is now covered by the lake.

Plate 39

Crescentic dunes in Carrizo Sands, moving to northeastward.

Moist dunes in Carrizo Sands, bearing mesquite and cats-claw, *Covillea*, nearly uprooted by action of wind in foreground.

During periods of high water the flood passes close against the eastern base of the southern end of this range and spreads out as it passes the southern end to cover a bare clay plain 6 to 15 miles wide, and by a slow current finds its way northward into a bowl-shaped depression, which has been designated the Pattie Basin, and the lake thus formed has long been known to the Indians as Laguna Maquata.

As the flood-waters pass down the slope to the laguna a series of channels have been eroded in the clay, which are known as Los Barrancas. The whole system offers a general parallel to the Salton Basin and Salton Lake. Between the two the Cucopa Mountains form a peninsula connected with high land by a strip running northwest across the international boundary.

The bases of the granite slopes are fringed with palo fierro (*Olneya tesota*), while *Terebinthus*, *Gaertneria*, *Opuntia bigelovi*, *O. prolifera*, *Cactus*, and *Echinocactus* find suitable habitats to within a few feet of the summit, at 3,500 feet altitude. At various places in the granite and conglomerate water collects in cavities and pools, forming tinajas, some of which are fairly permanent with the limited demand made upon them.

No exact study has yet been made of the flora of the Cucopa Range, but the preliminary examination seems to show several endemic species and that in general the forms present belong to the mainland to the eastward, although a careful analysis may reverse the latter inference. A single colony of palms (*Neowashingtonia*) is reported from a spring high up in a branch of a large canyon on the eastern side of the range.

The Pattie Basin offers some of the most interesting combinations of salt lake—of widely varying level—and desert yet examined. The extreme limit of the lake is 30 miles in length and 15 in width, but this limit is reached only on rare occasions. Marking the upper shore of the lake is a belt of mesquite from a few yards to a half mile in width, except where the lake comes against the granite slopes. Inside of this are several minor beach-lines which show that this lake refills quite frequently, much more so than Salton Lake (plate 43).

The beach of two years since is occupied by a zone of *Sesuvium sessile*, indicating a level at which the lake stood for a few months. With the cessation of the inflow, however, the decrease takes place rapidly, with deposition of salts, so that occasionally there is presented a bare desert with an area of 500 square miles absolutely devoid of vegetation, resembling in some respects the desert near Great Salt Lake. The movements of the fringing zones of vegetation will form a subject for investigation by the staff of the Desert Laboratory in conjunction with similar studies in the Salton Basin (plate 44).

The expedition to this region in February, 1907, encountered a thermal spring, the water of which showed temperatures from 112° to 128° F. at the margin of the lake. The surface of the warm pools was matted

with a felt composed of two algæ, *Phormidium tenue* and *P. tenuissimum*, both of which are identical with or nearly related to forms in the Hot Springs of Yellowstone Park. The water of the spring was also inhabited by a small rain-water fish. Specimens of this were submitted to Dr. D. S. Jordan, of Stanford University, who found that it belonged to a hitherto unknown species; and it was given the name of *Lucania brownii*, in honor of Mr. Herbert Brown, a member of the expedition. A dozen of these fish, taken from the spring, were placed in a vessel of water which cooled to air temperatures during the day and the following night without apparent discomfort to the animals. The water of the spring itself is highly charged with several salts, of which chloride of lime is one of the most abundant. It is to be seen, therefore, that this fish not only endures a water highly charged with salts, but is also capable of accommodating itself to great range of temperature. The entire spring is submerged to a depth of a half foot by the waters of the laguna at flood.

THE SAN FELIPE DESERT IN BAJA CALIFORNIA.

The western shore of the Gulf of California is made up of a continuation of mud flats and saline plains for some distance south of the mouth of the Colorado River. South of this formation the gravelly slopes and granite and volcanic ridges of the mountains come out to the shores, and here, to the leeward of the main ridge of the peninsula, are to be found some of the most arid conditions in North America (plate 45).

The central elevation consists of the mountain ridge which culminates in the peak of Calamahuie at an elevation estimated at 10,000 feet. To the eastward it breaks into lofty precipices and steep slopes which have not been surmounted between 30° 30′ and 32° 30′ N.

The lower coastal slopes are sandy and gravelly, the depressions and dunes near the shore furnishing suitable conditions for *Lycium torreyi* (plate 47) and *Parosela spinosa*, which latter becomes a tree 25 feet in height. *Ascelepias subulata* was abundant in clumps, and *Ditaxis serrata* grew on level areas. Other species which were characteristic of the lower levels were *Ibervillea* sp., *Croton californicum*, *Lupinus mexicanus*, and the curious *Frankenia palmeri.*. The low alkaline pockets reached by the spring tides furnished conditions suitable for *Spirostachys occidentalis*. *Covillea*, with its enormous capacity of adjustment, extended from near the shore across the entire slope and up the granite mountains through a range of over 2,000 feet in elevation. The various portions of the slope between the sea and the first range of coastal mountains supported ocotillo (*Fouquieria splendens*), which attained its maximum height of 30 feet, palo verde (*Parkinsonia microphylla*), palo fierro (*Olneya tesota*), and *Gaertneria ilicifolia*. On an expedition to this place in 1904 a new copal tree was found, *Terebinthus macdougali* (plate 46), which also is now known to occur on the eastern shore of the Gulf, and which secretes a

resin so copiously as to make a distinct deposit on the ground underneath the low-spreading branches.

The streamways leading down from the mountains were inhabited by a number of eriogonums and euphorbiaceous herbs. A few opuntias of the cylindrical arboreous type (plate 47), an *Echinocactus*, a *Cactus*, and a small *Cereus* were also seen. *Pilocereus sargentianus*, which is found on the mainland far southward, here reaches the greatest density yet observed, forming forests many acres in extent. Perhaps the most notable feature from a geographical point of view was shown by the presence of a great tree-cactus having the appearance of *Cereus pecten-aboriginum*. *Cereus pringlei* is known to be abundant, under the common name of "cardon" farther south, but this plant appears to agree with the former and makes a splendid picture in the arid landscape, finding here its extreme northern limit of known occurrence.

The large number of species with laticiferous juices was especially noticeable, but with the exception of the dozen cacti no plants with organs for storage of water were seen, a fact possibly connected with the extremely low precipitation and low water content of the soil at all times. Seeds of a *Cenchrus* were very abundant and were used by burrowing rodents as a means of fortification of the entrances to their burrows, in the same manner that the joints of the "cholla" are employed elsewhere.

A mountain to the southwestward of San Felipe Bay was climbed and a summit reached at an elevation of about 3,500 feet. The granite slopes supported a sparse vegetation of such types as *Cactus*, *Ephedra*, *Terebinthus microphylla*, *Asclepias albicans*, *Eriogonum inflatum*, *Yucca*, *Agave*, and *Opuntia*. So far as might be estimated by the instruments at hand, the mountain is probably the one on the hydrographic map of 1873-75 designated as a "sharp white peak 4,288 feet," which had not previously been ascended and still bears no name.

The rainfall is apparently distributed throughout the year, so that only a small proportion of the total is received within any month; furthermore, this distribution is irregular in any series of seasons, so that the native plants have but little opportunity of acquiring a rhythm of activity in response to the annual supply of moisture, a fact not without its influence on the general anatomical character of the plants.

Dr. Edward Palmer visited the Raza Islands, in the lower part of the Gulf, 200 miles northwest from Guaymas, in February, 1890, and noted that no rainfall had been received there for more than a year. Nothing can be hazarded as to the extent of the region with this extreme limit of aridity on the Sonoran side of the Gulf, except that it does not appear to include the western slope of the central range in Baja California, although no definite information is available. It is evident, however, that a further investigation is necessary to determine the exact meteorological status of this region, as well as the general character, derivation, and

relationship of its flora. The extreme type of strict desert offered by the area in question points to the possibility of finding here the readiest solution of some of the more important problems presented by desert vegetation.

TUCSON, THE SITE OF THE DESERT LABORATORY.

In the original selection of Tucson as a laboratory site the following conditions were taken into consideration as being desirable:

1. A distinctly desert climate and flora.
2. A flora as rich and varied as possible, while still of a distinctly desert character.
3. Ready accessibility.
4. Habitability.

Much of the arid region of the western United States is only partially or relatively arid and does not therefore contain those pronounced types of drought-resistant vegetation which it is the first object of the Laboratory to investigate. Such semi-desert areas are the western portions of Kansas and Nebraska, and the intramontane valleys of southern California. Another sort of location, to be avoided for a like reason, was a desert which was likely to be reclaimed by irrigation. The desert character of a small area, even though carefully reserved, might be seriously modified by seepage or other changes following irrigation development in the vicinity.

Some of our deserts, such as the Mohave, the Colorado, and the lower part of the Gila, are of such extreme aridity that only a small number of vegetative types occur in them. The same paucity of vegetative types is usually characteristic of any flat area of desert as distinguished from a foothill, canyon, or mountain area, a broken and rocky soil giving a wider range of temperature and moisture conditions of both soil and air, and furnishing lodgment for a greater variety of plants. The yucca plains of the Otero Basin in New Mexico and the sage plains along the Snake and Columbia rivers in Idaho, Washington, and Oregon are examples of deserts in which a pronounced paucity of woody species is correlated not with extreme conditions of aridity but with flatness of surface.

The conditions of living at some spots in the desert suitable in other respects for laboratory purposes are so severe as to offer an obstacle to the best work. A period of such extreme heat as occurs in summer at some points of very low elevation, as for example, along the lower Colorado River or in the vicinity of Guaymas, Sonora, or the difficulty of getting pure water and good food, has been an effective argument against some otherwise good locations.

Viewed from the standpoint of these primary requirements, Tucson has a climate of a thoroughly desert character, and a flora, including mountains and plain, rich in species and genera. In addition to its situation in the heart of the desert of Arizona, it is centrally located, both as to

Plate 41

Shore of Salton Lake in May, 1906, at which time the level was rising at the rate of 6 inches daily.

Plate 42

Ancient beach line of Salton basin denoted by terrace on right. Lake at maximum height, February, 1907. The vegetation is arranged in bands denoting minor beaches.

Plate 43

Pattie basin, looking northwestward across the Laguna Maquata. *Sesuvium sessile* or sea-purslane in foreground.

Eastern margin of Pattie basin and Cucopa Mountains. Sea-purslane (*Sesuvium sessile*) in the foreground, denoting recent level of the Laguna Maquata. Next to it is a zone of salt-bushes (*Atriplex*), then mallows and shrubs, while a zone of mesquite denotes the maximum level of the water.

position and transportation, with reference to the deserts of Texas, Chihuahua, New Mexico, California, and Sonora. The city has a population of nearly 22,000. It is situated on one transcontinental railway, and has good connections with others, as well as shorter lines to various regions of interest.

The business of the city and the conduct of its municipal affairs are largely in the hands of progressive Americans. The elevation of Tucson is 2,390 feet, while the highest of the mountains that surround the plain in which the city lies, the Santa Catalina Range, reaches about 7,000 feet higher. The University of Arizona, with its School of Mines, and the Arizona Agricultural Experiment Station are located at Tucson.

Not the least of the advantages of Tucson as a center for the activities of the Laboratory is the broadminded comprehension of the importance of the purposes of the institution evinced by the citizens, accompanied by an earnest desire to coöperate in its establishment. This appreciation was expressed in the practical form of subsidies of land for the site of the building and to serve as a preserve for desert vegetation, the installation and construction of telephone, light, and power connections, and of a road to the site of the Laboratory, about 2 miles from Tucson. The monetary value of these concessions is by no means small, and is much enhanced by the generous spirit in which they were tendered. This spirit of hearty coöperation has animated every organization in the city, and has enabled the Laboratory to gain control of a domain of 860 acres, of the greatest usefulness for general experimental work (plate 48).

GEOLOGICAL SKETCH OF THE REGION OF TUCSON, ARIZONA.*

PHYSIOGRAPHY AND GEOLOGY.

The valley of the ancient Pueblo of Tucson, in Pima County, Arizona, is an expanded portion of the valley of the Santa Cruz River. This stream has great historic interest as one of the most direct routes by which the early Spanish explorers made their way from Mexico into the then unknown regions of the north. At Tucson the river occupies the western side of the valley at the eastern base of the Tucson Mountains, and flows northward toward the Gila River, but sinks in the sand before reaching it. In seasons of little rain it is an insignificant stream, but is subject to great floods in the rainy seasons, which sweep away acres of rich alluvions and change the position of the main channel. The city of Tucson is built upon the right bank of the stream, and Tumamoc Hill, the site of the Desert Laboratory, is on the opposite or left bank.

The broad valley of Tucson has the appearance of being surrounded by mountain ranges on all sides. The view on the north and northeast is

* Prepared by request and contributed by Prof. Wm. P. Blake, Sc.D., LL.D., Territorial Geologist of Arizona.

bounded by the high and rugged range of the Catalina Mountains and their continuation southward known as the Rincons, on the east and south by the Whetstones and the Santa Ritas, on the southwest by the Sierritas, and west by the Tucson Mountains, of which Tumamoc Hill is an outlying spur. The Tortolita Mountains, a detached group of mountains lying west of the Santa Catalina Mountains, may be regarded as forming a part of the northern and western boundary of the valley. The region so apparently inclosed by mountains has an approximate breadth of 18 to 30 miles; a length of 40 miles; in the aggregate an area of over 1,000 square miles. The elevation is generally from 2,400 feet above tide at Tucson to 3,500 feet at the upper margin of the detrital slopes bordering the higher ridges.

From this upper margin, the ground descends toward the Santa Cruz River, and in the middle and lower portions constitutes what is known as the "mesa," apparently a great plain but in reality a continuous slope, modified locally by the erosion due to the rains and rivers. In traveling over the lower portion of the extended mesa, the horizon line appears perfectly level, like the horizon line at sea.

There is a great variety in the age and the composition of the rocky ridges, which, rising to a height of 5,000 feet or more above the general level of the mesa region, give a wide range of climatic conditions and of vegetation. In the season of winter rains in the valley, the summits receive a coating of snow which by gradual melting maintains a supply for springs and rivulets until the season of summer rains.

The principal streams of the region, in addition to the Santa Cruz, are the Rillito, at the foot of the Catalinas, north of Tucson; the Pantano Wash, rising in the Whetstone Mountains east of the Santa Ritas, receiving several accessions, including Rincon Creek and an underground flow of Davidson's Canyon.

The principal canyons of the south slope of the Catalinas are the Pima, Ventana, Sabino, Bear Canyon, Soldier's Canyon, and Agua Caliente. The Sabino with Bear Canyon drains an extended portion of the pine-forest region of the summit and has running water throughout the year, which it is proposed to utilize for power and water for the city of Tucson.

The Ventana Canyon is so named from the peculiar window-like opening through the rocks at the crest of the mountain. The opening is visible from Tucson.

THE SANTA CATALINA RANGE.

The Santa Catalina Mountain range is one of the most prominent and picturesque of the central mountain system of Arizona. It presents a bold rocky front towards Tucson, and rises to an altitude of 9,125 feet in Mount Lemon and to 9,225 feet in Mount Rice. Its general trend is northwest and southeast. Considered together with the Graham Moun-

tains, a high and nearly parallel range farther east, they represent a large part of the southward continuation of the Bradshaw Mountains of Central Arizona.

The central nuclei of these ranges consist of crystalline rocks, chiefly granitic and gneissic.

The rock formations on the southern side of the Catalinas, toward the valley of Tucson, are for the most part pre-Cambrian gneiss and mica-schists in tabular form, regularly stratified and with included sericitic schist, all believed to represent some of the oldest rocks known, equivalents of the ancient Huronian, the Keweenawan, and Laurentian formations of Canada.

The complete penetration of the schistose slates by veins and layers of potash or soda feldspar, forms what is known as "augen-gneiss," so called because of the many white protuberances on the surfaces. This rock, particularly near the mouths of Sabino and Bear canyons, can be broken out in tabular masses well adapted to constructive purposes. It also can be quarried in prismatic or post-like blocks from 3 to 4 feet long, such as were utilized by the prehistoric people for foundations of houses by setting them upright in the ground, as may be seen in the remains of an extensive village at the mouth of Bear Canyon.

Pre-Cambrian gneissic rocks are also largely developed on the northeastern flanks of the Catalinas, and are there associated with highly laminated mica-schists; the Arizonian, a formation largely developed at several widely separated localities in southern Arizona, notably at Pinal and the Salt River Valley. These schists are characterized by extreme foliation and sharp angular plications presenting zigzag lines upon exposed surfaces.

Here also, on the northeastern side of the Catalinas, we find Paleozoic strata resting uncomformably upon the crystalline schists of the pre-Cambrian, or upon a broad area of coarse granite as at Oracle and at the sources of the Canada de Oro on the northeast side of the range.

The foundation granites are penetrated by great dikes of diorite which, coming in contact with limestone of a dark bluish-gray color, have changed it to a crystalline white marble, seen to good advantage at Giesman's Camp and Marble Peak. Copper ores are developed along the contact, notably at the Apache Spring and Leatherwood's Camp.

DEVONIAN ROCKS.

Between the Southern Belle Canyon and Pepper-Sauce Gulch, a high and long ridge extending eastward and named Coral Ridge is made up of quartzite, limestone, and shaly limestones in which there is a bed of corals and shells of Devonian age. These fossils are interesting, not only as evidence of the geological age of the rocks and records of the life of that early period, but for their wonderful preservation in every detail

of structure. This preservation is due to the permeation of the rock by silicious waters which have changed the organized structures from carbonate of lime to silica, while the investing, or surrounding, limestone remained unchanged. The fossils thus became silicified and then, being less soluble than the limestone, are left by the weathering standing out above the general surface in bold relief.

Silicified fossils in limestone are common at many localities in Arizona.

A fine section of the stratified rock formations of the northern end of the range is found along the Southern Belle Creek, which extends from the summit of the range eastward. The strata are uplifted and dip eastwardly at an angle of about 15 degrees. The series consists of regular strata of red sandstone and shale, quartzites, sandstones, and limestone, resting upon diorite at the west end, where also we find a strong vein of auriferous quartz traversing the red rock approximately parallel with the contact. At the eastern end of the section strata of sandstone and limestone abut upon granite and are much altered in composition. These limestone beds are the upper members of the series of the section and are probably Devonian, as indicated by beds of corals. The underlying strata of sandy shales are distinctly fucoidal. The most prominent strata of the series are the massive white quartzites, with repeated outcrops due probably to faulting. The red shales of the lower series pass into beds of red sandstone of compact and even grain, regular freestone, suitable for buildings. The underlying diorite penetrates this series of shales and sandstones and is itself underlaid by the coarsely crystalline porphyritic gray granite which is largely developed around the northern portion of the Catalinas, extending to Oracle and beyond. It has a wide extension toward the east and north, reaching nearly to the San Pedro River, and on the west it extends to the Canada de Oro, where strata of quartzite and limestone rest against it. At and near Oracle the granite weathers into huge boulders of decomposition, giving a very picturesque and diversified surface overgrown by groves of evergreen oaks.

There are several localities of remarkable conglomerate in the northern and central portions of the Santa Catalinas. The component pebbles are chiefly from quartzite; they are all much rounded and show the violent action of currents and waves indicative of shallow seas and insular conditions in remote geologic time.

THE RINCON RANGE.

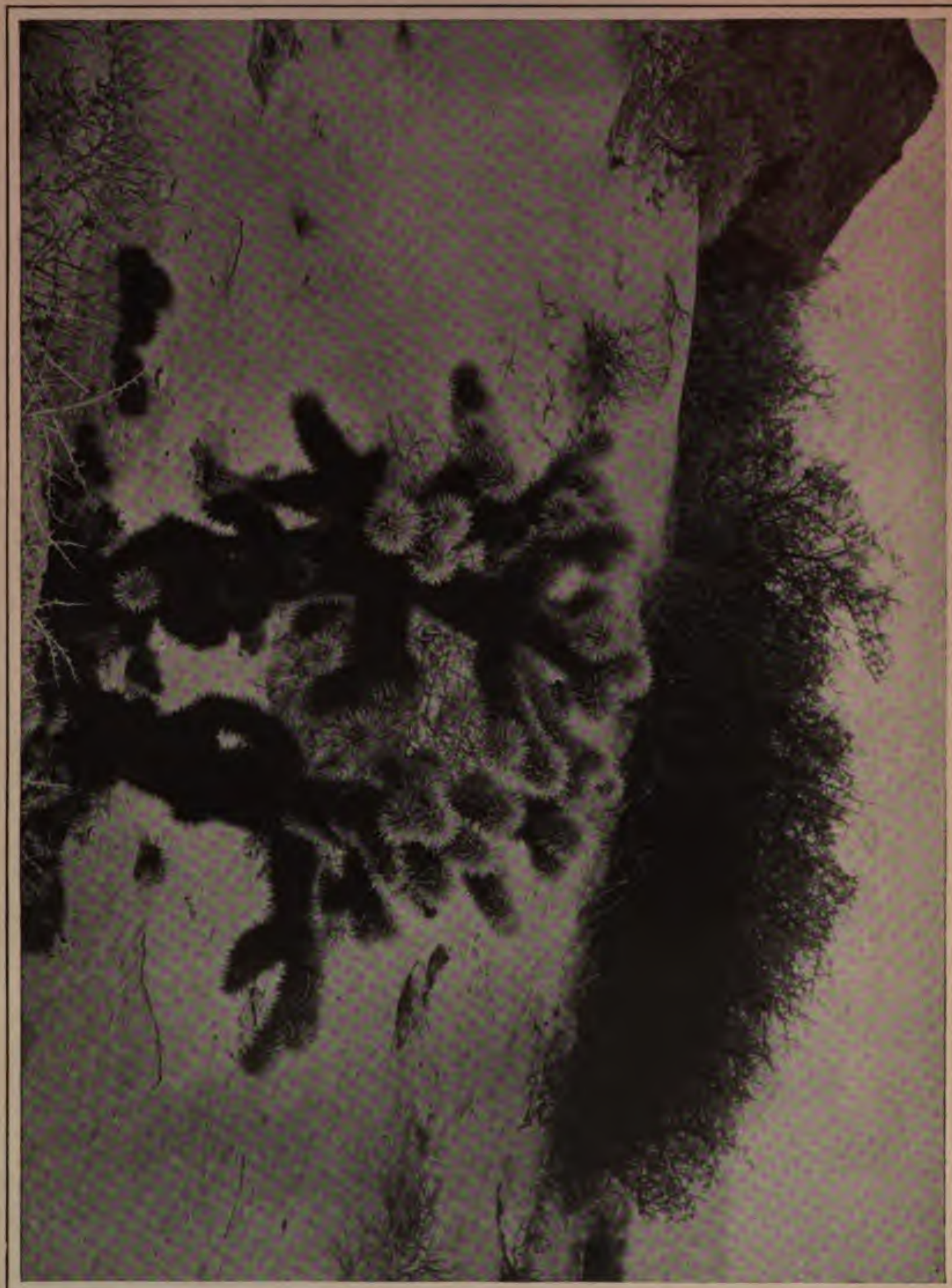
In the southern prolongation of the Catalinas known as the Rincons the central and higher portion consists of gneissic rocks like those of the Catalinas, but toward the railroad pass to Benson these crystalline rocks are flanked by an extensive development of Paleozoic strata, chiefly quartzites, shales, and limestones uplifted and contorted, and underlaid by a coarse granite. Silicified corals abound in places and indicate a

Desert of San Felipe de Jesus, Baja California. Ocotillo, creosote-bush, chamiso, and copal-trees.

Plate 46

Copal-tree (*Terebinthus macdougali*) of desert of San Felipe.

Plate 47



Devonian horizon above the basal quartzites, which are probably Cambrian in age.

The plutonic rocks are represented by intrusive dikes traversing the older crystallines. There is good reason to believe upon stratigraphical and lithological evidence that the Carboniferous and the Jura-Trias series and later Secondary rocks are developed in the region between Vail's Station and the summit of the railway pass leading over to the valley of the San Pedro.

THE VALLEY OF THE SAN PEDRO RIVER.

The geographic and geologic relations of the valley of the San Pedro to the Tucson region are such as to require more than a passing allusion. This valley east of the Santa Catalina Mountains was once the bed of a lake-like or estuarine sheet of water, described in 1902 and named Lake Quiburis.*

The San Pedro River, anciently the Quiburis, though in times of drought a small and insignificant stream, drains a considerable area, and is bordered throughout its course by mountain ranges forming a valley from 10 to 20 miles in width and nearly 150 miles in length. The chief ranges on the right bank, or eastern side, are the Mule Mountains (Tombstone), the Dragoons, and the Galiuros; and on the west, the Huachucas, the Whetstones, Rincons, and Santa Catalinas. The valley is in general parallel with that of the Santa Cruz, the next great valley to the westward, and with the Sulphur Springs Valley eastward. This river has cut its way through extensive horizontal beds of unconsolidated light red clays and sediments of great thickness, often terraced by the river erosion and extending high up on the sides of the bordering mountains. One of the best cross-sections is found on the line of the Southern Pacific Railway, which crosses the valley nearly at right angles to its course at Benson.

Benson, in the bottom of the valley, has an altitude of 3,576 feet above the sea. The river is about 50 feet lower. The lacustrine clays rise from this point on each side to the height of about 3,000 feet. The exact limit of clay deposition is not easily determined. It appears most probable that the height of the water was about 4,000 feet above the tide. Wells bored in the valley pass through similar sediments for 500 feet without reaching bed-rock.

---

*Lake Quiburis, an Ancient Pliocene Lake in Arizona. *University of Arizona Monthly*, vol. IV, No. 4, February, 1902. A paper read by invitation at the meeting of the Cordilleran Section of the Geological Society of America at Berkeley, California, January, 1902.

"Rio Quiburis, now more generally known as the San Pedro, was explored in 1697 by a party of 20 men and a sergeant, commanded by Cristobal Martin Bernal, who was joined at Quiburis Rancheria by another party under Kino. The united force, with 30 Indians, marched down the river to the Gila, thence to Casa Grande and returned up the Santa Cruz." (Bancroft's Works, vol. XVII, pp. 355–356).

The extensive strata of diatomite and volcanic ash, upward of 100 feet thick, are cut through by the San Pedro, exposing a succession of snow-white cliffs.

THE SANTA RITA RANGE.

The elevated and picturesque range on the east and south side of the valley of Tucson is noted for its rugged outline and sharp summit, known as Wrightson's Peak or Old Baldy, rising to an elevation of 9,432 feet, on which, in the rainy season, clouds are the first to gather like storm signals, and in the winter season its peak is the first to become whitened with snow.

This range extends in a general northerly direction from Patagonia, on the Sonoita, in Santa Cruz County, to the Rincon Mountains, a distance of nearly 40 miles. It is characterized by a great diversity of rock formations—granitic, volcanic, plutonic, and sedimentary.

Its northern portion consists of a broad development of Paleozoic strata in a succession of hills and ridges eastward to the Whetstone Mountains, which border the valley of the San Pedro. Southward toward the Box Canyon the strata, consisting chiefly of red shales, limestone, and a basal quartzite, are uplifted at high angles and form the crest of the range, resting upon granite and facing the valley of Tucson, as at Helvetia, where copper ores are mined near the contact of the strata with the granite. The quartzites are probably Cambrian. Their outcrops form a sharp ridge with a serrated outline, as seen from the valley of Tucson.

The Box Canyon is a notable geologic feature, bisecting as it does the entire range from east to west like a gigantic vertical cleft, and probably follows an east and west faulting plane. It drains an extensive area on the eastern side toward Rosemont and Greaterville, but delivers its waters into the Santa Cruz Valley on the western side. It exposes the edges of inclined strata right and left, but especially on the south side, where we find the succession of strata to be approximately as follows:

At the base is a massively brecciated granite, with small veins of gold-bearing quartz. Resting upon this granite and dipping east we find a conglomerate and coarse sandstone succeeded by red shales, sandstones, and limestones and a conglomerate of limestone pebbles resembling a conglomerate in the Huachuca Mountains. The limestone beds near Greaterville contain fossils of the Devonian age.*

South of the Box Canyon the structure of the Santa Rita becomes much more complex. The Paleozoic sandstones and limestones resting upon a granite foundation give place to granite hills and rocks of volcanic origin chiefly in the form of rhyolitic tuffs, consolidated ashes, agglomer-

*For a list of fossils and other data concerning this section of the range reference is made to a paper in the *American Geologist*, vol. XXVII, March, 1901.

ates, and porphyries. These formations of volcanic origin appear to constitute the bulk of the main range south of Greaterville and to extend to the very summit of the highest peak.

The detrital bordering slopes so characteristic of the mountain ranges of the Southwest are well developed on both sides of the Santa Rita, not alone toward the Santa Cruz on the west, but on the eastern side north and south of Greaterville, where there are extensive detrital deposits of great thickness and regularity of slope. This formerly continuous slope is now cut through by several channels due to modern drainage, and these trenching channels, or washes, of reassorted gravels and coarse detritus of the ancient slopes are found to be gold-bearing and have been largely worked.

On the western side of the Santa Ritas, south of Box Canyon, there are several deeply cut valleys. A wide and deep valley between Old Baldy and Mount Hopkins is drained by Madera Creek, which rises in Santa Cruz County.

The celebrated large ring meteorite known as the Irwin-Ainsa meteorite, now in the National Museum at Washington, was found at the mouth of this canyon.

Still farther south Montosa Creek, nearly opposite Tubac, cuts through the most western of the rock exposures at the head of the slope and reveals strata of compact blue limestone trending northwest and southeast and dipping westerly about 45°. It contains obscure brachiopod fossils. It is underlaid conformably by a thick series of red shales which in turn rest upon a pegmatoid granular granite with very little or no mica. A diagrammatic sketch section across the cropping shows the relations of the rocks.

There are intrusions of porphyry in dikes which have changed portions of the blue limestone to white and the red shales in great part to green epidote associated with beds and seams of specular iron. These shales are estimated to have a thickness of over 500 feet. They become more sandy and granular, like sandstones, near the granite. They may be known by the name of the locality, as the Montosa shales. The pegmatitic granite, against which these formations lie, contains in places pyritous impregnations without distinct veins. These sulphides on decomposing give rusty outcrops and gold is liberated in fine grains.

Montosa Creek brings down from the high ridges a great variety of crystalline rocks, in boulders, such as granite, syenite, gabbro, and feldspar-porphyry. At the south end of the higher parts of the range there is an extensive development of intrusive diorite with many mineral veins and mines, known since the occupation of the country as the Saléro. This diorite is partly overlaid on the east and south by the extensively developed stratified tufas of the Santa Rita series. They consist of granular mixtures, agglomerations, and breccias of rhyolitic volcanic porphyries, pumice, and volcanic ash.

At the base of the highest peak of the Santa Rita and underlying the tufas, there is one of the most remarkable beds of large rounded boulders of porphyry known. It is exposed to view for a mile or more by the excavation of an aqueduct for the conveyance of water for the placers at Greaterville. The boulders vary in size from a few inches to a yard or more in diameter. They are of various colors, are closely compacted, and form a thick bed at a low horizon in the series and may be regarded as evidence of stupendous cataclysmic action.

At Poston's Mountain and Mount Allen and in the Grosvenor Hills, southwest of Saléro, there are remarkable strata of snow-white tufaceous flagstones so thinly and regularly stratified that slabs yards in area and only a few inches thick may be broken out. These tabular masses are well fitted for pavements or for building walls. They show ripple-marks on their surfaces and little annular projections around what are seemingly little pebbles which had fallen upon the surface of the rock when it was in a plastic state or in a thick creamy consistency left by a receding tide. The whole series gives evidence of deposition in shallow water, and this is shown elsewhere by regular bedding and stratification of the Santa Rita tufas.

SANTA RITA TUFAS.

At the peculiar outcrop of rock west of the arroyo of Josephine Canyon and at the head of the great slope down to the Santa Cruz at Tubac the tufas from the Santa Rita are in massive and horizontal beds, regularly stratified and made up of granular and generally rounded fragments of rhyolites and porphyries cemented together with volcanic mud or volcanic ashes. The regularity of the stratification and the average composition is such that pillars are left standing by the weathering away of the surrounding rock, and hence the name Los Pilares. The formation appears to have a wide extension. It underlies the ancient detrital slope which is spread out over it, except where removed by stream erosion.

The high peak of the Santa Rita with its enormous flanking ridges of volcanic ejecta is certainly a monumental relic of a great center or region of volcanic activity from which an immense volume of broken rock, rhyolites, and ashes was spread far and wide. No distinct crater has yet been found, but there is a broad area between the higher peaks which has not yet been explored. We are at least certain that in the Santa Rita we have an ancient uplift of a thick series of tufaceous and rhyolitic deposits at higher levels than in other localities in the region.

The evidence is conclusive that the greater part of this vast mass of volcanic ejecta was spread under water. We not only have the stratification of the beds of the Santa Rita, but of its many spurs and of the distant ridges of the Grosvenor Mountains, where the white feldspathic flagstones are covered with ripple-marks.

Desert Botanical Laboratory.

Papago house built of ribs of saguaro (*Cereus giganteus*) with corner-posts of mesquite (*Prosopis*), near Desert Laboratory.

Tumamoc and Sentinel Hills from the southward, with the Santa Catalina Mountains in the distance across the valley of the Santa Cruz River. Vertical section in lower figure.

Plate 50

Western end of Santa Catalina Mountains, showing flanking slopes.

Slope of the Sierritas as seen from the Tucson Mountains.

We can not doubt that the enormous deposits around the Santa Rita are of remote antiquity, probably pre-Tertiary, antedating the continental uplift at the close of the Miocene. They may be known as the Santa Rita tufas.

THE SIERRITAS AND THE TUCSON MOUNTAINS.

The mountains forming the southwestern limit of the valley and on the right bank of the Santa Cruz River are largely granitic, with strata of subcarboniferous limestone and shales partly metamorphosed and copper-bearing. The Twin Buttes copper mine is found here, and other mines at Mineral Hill, and at the Azurite Camp, all in association with porphyritic dikes and garnetiferous veins, the result of alteration of the limestone.

The Sierritas give place farther north to the Tucson Mountains, composed in great part, opposite Tucson, of volcanic tufas and agglomerates, forming hills of very picturesque and uneven outline, as may be seen by reference to plate 51, made from a photograph taken a mile or two south and west of the Desert Laboratory. These tufas are regularly stratified and are upraised. They are probably pre-Tertiary or Cretaceous in age, the equivalents in this respect of the stratified tufas of the Santa Rita Mountains on the opposite side of the valley. Similar tufas are found as far south as the Cerro Colorado and beyond toward Nogales and Sonora, Mexico.

The prolongation northward of similar rhyolitic tufas is found beyond Tucson, especially in the foothills bordering the Santa Cruz, where there are extensive outcrops of stratified tuffs, rhyolites, and andesitic rocks which are uplifted at various angles.

At the Pictured Rocks the stratification is very distinct, with ripple-marks upon the surfaces of the slabs of rock, which have the composition of porphyritic andesite. These rocks are near the Old Yuma Mine, opened upon a quartz-vein bearing lead-ore and gold.

The western portion of the Tucson Mountains is made up in part of ancient sediments of Paleozoic age—limestones, sandstones, and shales. Blue limestone, probably lower Carboniferous, much traversed by flint, crops out in Snyder's Mountain, and is quarried and burned for lime. There are plutonic rocks in great variety in the form of dikes.

A fine-grained gray andesite in the hills west of Tucson affords an excellent building stone, used especially for rubble walls.

The extensive rhyolitic intrusions north and south and on both sides of the Santa Cruz Valley command attention as marking a long line of disruption and faulting of the crust, accompanied, no doubt, by crustal movements at different periods, parallel to the axes of the uplift of the Paleozoic strata. The more distinctly characterized and more fusible volcanic rocks, less viscid than the older rhyolites were, are of a later age

and are present in the form of basaltic lavas spread out originally in great sheets in igneous outpourings upon the upturned edges of the rhyolites and other rocks, as, for example, in the Galiuro Mountains east of the Catalinas. Remnants and detached areas of such floods of liquid lava are found at the western side of the Babiquivari Valley, at the Mission of San Xavier, 9 miles south of Tucson, and at the Sentinel and Tumamoc hills opposite the city.

TUMAMOC.

The Tumamoc group as seen from a point a few miles north shows two summits, one rising in conical form from the Santa Cruz and known as Sentinel Peak; the other has a broad, flattened summit of greater area and is connected with the peak by a long, comparatively level ridge. The flat-topped Tumamoc Hill is formed largely at the surface of loose rough blocks of basalt anciently used by the aborigines for the construction of a rude fortification as a place of refuge when driven by roaming bands from predatory tribes from their fields and dwellings on the fertile bottom-lands of the Santa Cruz.

A great number of partitions of rude apartments inside of the circumvallation indicate that many people made their homes, for a time at least, upon this rocky summit, 700 feet above the valley.

The buildings of the Desert Laboratory are upon the northern slope of this hill, about half-way down and at an elevation of 329 feet above the Santa Cruz River, and, like the prehistoric fortress, are built of the loose boulders of basalt which abound upon the surface.

These basaltic hills, of which Tumamoc is one only of a series, present to the eye a black, barren rocky surface, with but little visible soil or earth for the support of the scanty but peculiar vegetation which finds a foothold in the clefts and crevices.

That these rocks are volcanic in origin there is no doubt, but without any crater or indication, by form, of an extinct volcano. There is evidence in the structure and the interstratification of beds of tufa, and in the amygdaloidal interior structure of the basalts, of an igneous outflow from some higher ground, but satisfactory evidence of the source has not yet been found.

The basalts of Tumamoc and of Sentinel and southward to the Mission present a variety in chemical composition and structure, giving evidence of flows or outpourings of different ages. These rocks have been carefully studied petrologically by Prof. F. N. Guild, of the University of Arizona, who finds three varieties: (1) Fine-grained olivine basalt; (2) porphyritic basalt with feldspar crystals; (3) quartz basalt.

In places, notably in the quartz basalt, on the southern base of Sentinel Peak, the amygdular cavities are filled with silica in the form of agate and also in the form of geodes.*

*American Journal of Science, vol. xx, October, 1906.

The photograph in plate 49, together with the diagrammatic sketch section, will serve to give an idea of the general outline of these hills and to show their geologic relation to the alluvions of the Santa Cruz River.

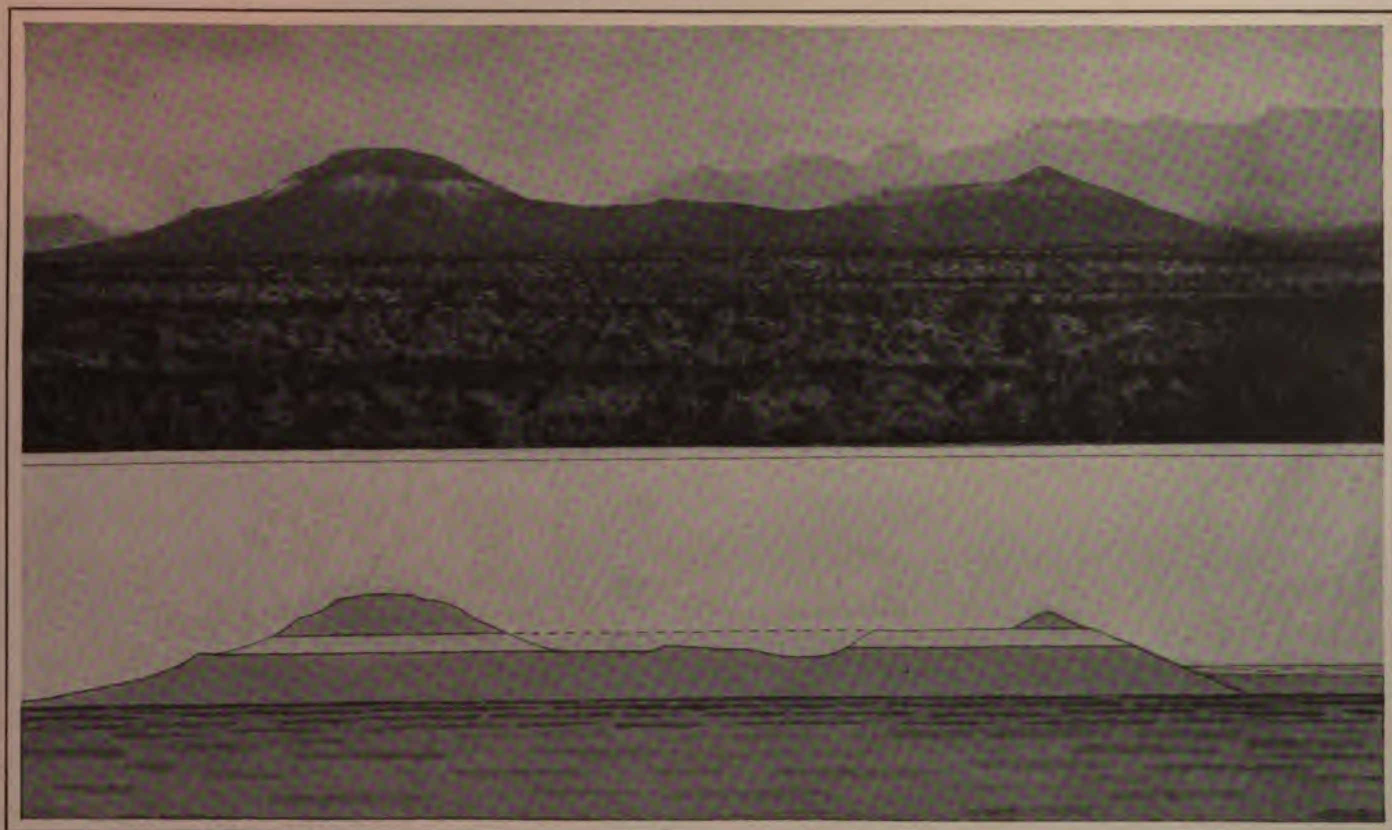
This section also shows the interstratification of a nearly horizontal bed of volcanic tufa capped by a basalt on both Tumamoc and Sentinel hills. This, which was doubtless a continuous bed, has been largely swept away by denudation, as indicated by the broken lines. The remaining portions of this tufa bed, protected by the overlying hard basaltic rock, were evidently spread out in the condition of plastic mud upon a foundation layer of basalt. It is now solidified and is sufficiently firm to be extensively used for building purposes. Its color is white or gray and it is thus in strong contrast with the black of the basalt.

There are several quarries of this tufa around Tumamoc Hill and at other places in this volcanic group. A quarry on the Quijotoa road near the Mission of San Xavier yields a light-gray, nearly white, building stone of excellent quality for construction. It supplied the stone for the large dormitory building at the university. This stone is essentially silicious in composition and includes in its substance angular fragments of rock, evidently broken by violence from their parent sources and borne along in the viscous mass. In the same rock we find interesting orbicular concretions consisting of concentric layers of different colors and chemical composition,* giving evidence of internal chemical changes around fragments of soluble rocks.

The tufa bed at Tumamoc is about 25 feet thick, so far as exposed. It has a slight easterly dip and passes under and through Sentinel Hill, forming the nearly level ridge extending between and connecting the two hills. It is underlaid by a bed of sandy material consisting of a mixture of grains of clear glass and fragments of feldspar. This vitreous sandy bed, some 6 feet or more in thickness, is in turn underlaid by a distinctly stratified body of small black, pebble-like but crystalline fragments of rhyolitic basalt in an earthy magma. It is a soft, unconsolidated substratum, which being easily removed by erosion hastened, by undermining, the downfall of the overlying basalt, which once covered the entire area of the tufa. This process of degradation, especially during partial submergence, would explain the origin of the great accumulation of boulders over the surface of both Tumamoc and Sentinel hills. The boulders are often so thickly laid down as to cover the solid basalt from view. In many places they are cemented together by caliche which has been deposited around them, forming a cemented aggregate of great hardness. The boulders have for many years been drawn upon for building purposes, particularly for foundations in the city. The walls of the Desert Laboratory are built of them.

*For a description of these orbiculites, see *Transactions American Institute of Mining Engineers*, May, 1905.

Plate 49



Tumamoc and Sentinel Hills from the southward, with the Santa Catalina Mountains in the distance across the valley of the Santa Cruz River. Vertical section in lower figure.

Plate 50

Western end of Santa Catalina Mountains, showing flanking slopes.

across the Santa Catalina slopes and leaves a steep bank for miles on the north side, as already represented. Similar conditions exist along the Santa Cruz opposite Tubac, where the ancient slope from the Santa Rita is cut across and shortened with the formation of high bluffs. In the deep arroyos trenching the slopes the nearly vertical banks exhibit rude stratification of gravels and sand, together with clay-like layers, not unlike the succession of gravels, sands, and clays revealed by the boring at the Esmond well.

FORMER LACUSTRINE CONDITIONS.

The evidences of submergence and uplift given by the detrital slopes are supported and strengthened by the phenomena of ancient lakes or estuarine deposits. These deposits show the long-continued existence of a large body of water with its surface at or about the 4,000-foot contour line.

The presence of a body of clay in the lower portion of the valley of the Santa Cruz at Tucson is evidence of the former existence there of a body of comparatively quiet water. It would appear that this deposit was anterior to the excavation or erosion of the river valley. It may be explained upon the hypothesis of a sink or depression at the intersection of the slopes from the Catalinas, the Rincons, Santa Ritas, and the Tucson Mountains, while the region was submerged. The uplift of the region and the advent of the Santa Cruz with the cutting down of its channel brought this clay deposit to view.

The excavation of a deep well for the city water-works passed through this clay and showed a heavy deposit of boulders below, marking an old channel. The trunk or large branch of a tree was also found, but in the condition of lignite, which speedily fell to pieces on drying.

These phenomena indicate a very ancient river-valley antedating the formation of the mountain slopes.

The fact of the submergence of the continent and its elevation above the sea in the late Miocene Tertiary is well known. There have been later changes of the relation of land and sea, but generally of less amplitude. Some of the effects herein attributed to oceanic action may date back to the earlier period of emergence.

The enormous volume of detrital materials filling the valleys and composing the slopes, whatever their relationship to oceanic distribution, bear testimony to long periods of erosion and degradation of the land and to eras of greater rainfall than we now have.

THE SOILS OF THE REGION.

The soils of the region of Tucson may be grouped in three classes:

1. The gravelly and sandy washes of the mountain slopes.
2. The red argillaceous deposits of the older slopes and of Tumamoc Hill and other hills of basalt.
3. The alluvions of the streams, chiefly of the Santa Cruz and of the Rillito.

The first class includes the detrital deposits of the mountain slopes, the boulders, gravel, and sands broken from the rocks of the ridges and spread out in the valley forming the "mesas." The area of such deposits is nearly that of the area of the valley. The deposits of the two other classes are really comparatively insignificant. As a general rule, the heavier and coarser materials are found near the mountains, while the finer gravels and sands are distributed at a greater distance and at the lower levels; yet large boulders up to 12 inches in diameter are found in digging wells far out on the mesa east of Tucson and south of the valley of the Rillito. The surface is generally free from large boulders or coarse gravel. A vertical section shows that the materials are rudely stratified, layers of coarse boulders, partly rounded, alternating with gravelly and sandy layers and with the red clays of class No. 2. There are also the included calcareous beds of caliche, and in places thin layers of gypsum. At a depth of 90 to 100 feet permanent water is found under the mesa slope for a few miles east and north of the city.

The surface earth of the mesa is essentially arenaceous and affords good natural roads. The prevailing color is white or gray, rather than red, though in some low places there are local deposits of red claylike loam, derived probably from the interstratified red clays of class No. 2.

There is a notable absence of humus in all the soils of this class. The conditions do not appear to have been favorable to the presence of organic matter in any form. Decay of vegetation, promoted by moisture, has not been possible. The nearest semblance to a soil favorable to vegetation upon the mesa lands about Tucson is found around and under the low-growing shrubs, which are important factors in the distribution and conservation of the sandy loams. This growth of plants, and especially that of the creosote bush, *Covillea tridentata*, not only protects the surface of the desert, so called, from the sweeping action of furious winds, but by checking the velocity of the wind causes the deposition of the wind-driven earth and sand about the roots.

RED CLAY SOILS.

The soils of class No. 2 are derived largely from the red argillaceous deposits interstratified with the gray gravels of the slopes. These red beds are most developed and visible in the section of the detrital slopes of the western end of the Catalina Range and on the road northward to Oracle. They are found at other localities where the detrital slopes have been cut through and exposed by erosion.

On Tumamoc Hill, although little can be seen beside the surface of black rock, the hill is not wholly without what may be called a soil—a soft brown-colored or red clay accumulation largely hidden under the loose rocks or in clefts and hollows protected from the washing action of rain. This red-brown clay does not appear to be the result of the decay of the rocks, but rather a residue of a once more extended deposit upon

the hill when under water. It much resembles the widely distributed red clay of the older slopes, but is darker in color.

Some soils or loamy deposits of the mesa have noxious qualities. A red-colored soil found in rather limited areas near to Tucson, for, example, in a strip a few rods long and wide on the grounds of the university, is noted for its infertility and the death of trees planted in it, although they are as well watered as trees a short distance beyond, which flourish luxuriantly. For convenience, it is designated as "red adobe." It is characterized by a large amount of sesquioxide of iron and by its compactness. A mechanical analysis reported by Professor Forbes* of a similar soil in which plants died, showed that it was more than three-fourths composed of coarse material, with one-fifth of silt and fine clay and very little organic matter. The same authority notes that an abundance of lime is characteristic of soils of arid regions and is one reason for the fertility of these soils under irrigation. It is also noted that such soils are deficient in nitrogen. The chemical investigations of soils by the Experiment Station have been mostly upon the soils of the Salt River Valley.

The general resemblance of the red clays of the slopes to the red argillaceous lacustrine beds of the ancient Lake Quiburis in the San Pedro Valley should be noted.

ALLUVIAL SOILS.

Class No. 3 includes the alluvions of the streams—the Santa Cruz, the Rillito, and the Pantano Wash. All are noted for their fertility and depth, requiring only water to produce abundantly.

The soils of the Rillito are more silicious, sandy, and feldspathic than those of the Santa Cruz, as would be expected from their source in the granite rocks of the Catalinas and the Rincons. The soils of the Santa Cruz are finer and darker in color and have their source, to a great degree, in the volcanic tuffs along the river from Nogales to Tucson, receiving additions from the granite and limestones of the Santa Rita and the Sierritas.

A deposit of calcareous clay already mentioned, in the lower part of the valley at Tucson, is indicative of a former lake-bed, or a formerly submerged area, at the lower intersection of the slopes; or, possibly, it may represent conditions analogous to those under which the playas of Nevada and of Arizona were formed, i. e., sediment from clay-laden meteoric flood-waters.

Several miles south of the Tucson region we find along the upper Sopori an extensive area of rich, dark-colored loam, evidently a deposit from a former fresh-water lake. The eastern barrier of the water has been lowered or swept away by erosion, permitting the drainage of the area.

---

*Arizona Agricultural Experiment Station Bulletin No. 28, March, 1898, p. 91.

CALICHE.

The widespread calcareous formation below the surface of the soil in the Southwest, known as ca iche, is a variety of travertine (carbonate of lime) of terrigenous origin and deposit. The composition of caliche, its form and distribution are factors of prime importance in any discussion of the growth and distribution of plants in regions where it occurs. Its influences in the soil are not only chemical but mechan'cal, and it exercises an important influence in the distribution of surfaces and underground waters.

Although the phenomena of distribution and the origin of caliche have been elsewhere described,* it seems appropriate in this place to review the principal facts relating to it, especially those which have a bearing upon plant-life.

The broad valley of Tucson affords good opportunities for the study of the phenomena of caliche, but although the deposit is generally present except in the bottom-lands, it is usually covered from view by a foot or two of earth. A furrow can not be turned by a plow without revealing it, and if trees are to be planted, the hole must be deepened by a sharp pick or by blasting. Caliche forms practically a continuous sheet, a foot or two under the surface, from 3 to 15 feet or more in thickness, of travertine-like lime deposit, with the more dense and impervious layers at the top. This upper surface is comparatively smooth, though undulating, and often has knob-like excrescences. In fracture the upper or thicker crust exhibits fine lines of edges of layers or successive coats, along which separation may take place. There is also a rude columnar structure transverse to the layers.

This hard upper crust, which seems like a layer of impervious cement, and which certainly retards the downward percolation of water, has, however, here and there minute perforations like pin-holes, at the top, which gradually enlarge downward and become lost in the more porous portions. These little holes are often occupied by the rootlets of plants.

This deposition of lime-carbonate appears to be the result of the gradual upward percolation of the calcareous phreatic water supplied from the subterranean streams, induced largely by the excessive surface evaporation under continued desiccating conditions. Its absence in the soil at the immediate surface may be explained as due to the solvent action of meteoric water soaking downward, carrying the lime with it.

Dr. B. E. Livingston in his discussion of caliche† has suggested that

*The Caliche of Southern Arizona, an example of deposition by the vadose circulation. *Transactions American Institute of Mining Engineers,* vol. XXXI, pp. 220–226, 1906.

†The Relation of Desert Plants to Soil Moisture and Evaporation, by Burton Edward Livingston. Carnegie Institution of Washington Publication No. 50, August, 1906, p. 8.

the upper layer is formed at the level where the water of the soil is vaporized faster than it can be supplied from below.

The conditions of the upward movement of the water must vary greatly with the subjacent supply and with the nature of the formation. Thus at the site of the Laboratory at Tumamoc the conditions of flow and moisture from below upward are very different from those of the gravelly plains of Tucson. The basaltic rock appears as an almost impermeable barrier to the upward flow of solutions, except where there are structural planes or seams and cracks, and it is in precisely such places we find the calcareous deposits on Tumamoc Hill, where also it fills fissures in vein-like forms. In one or more such fissures the deposit is in considerable quantity. Near the top of the ridge, on the east side, a large crevice or vein-like space is filled with the calcareous deposit and, having the semblance of a mineral vein, has been dug into by prospectors in the hope of finding valuable ore. The deposit is in successive layers on the walls and is like some of the deposits of lime-onyx, and is possibly in this instance the result of a downward flow of calcareous water in a fissure, supplied from the formerly overlying tufaceous deposits.

In ascending the north slope of the hill it may be noted that in places the otherwise loose blocks of black basalt are firmly cemented together with the lime deposit, so as to form a compact mass as if by the hands of a mason, as already described.

A similar cementation of boulders is found at the tufa quarry on the west side of the hill.

A chemical analysis of caliche, excluding the mechanically inclosed sand, shows the presence of:

Calcium carbonate	78.28	Aluminum silicate	7.37
Magnesium carbonate	2.13	Ferric oxide	1.88
Calcium silicate	5.57	Moisture	1.20

The concentration of salts more soluble than lime carbonate by surface evaporation in the dry season, such as salt, sulphate of soda, and in some cases carbonate of soda, or "black alkali," are other examples of the same conditions of origin. In the rainy season these soluble salts are carried downward and disappear in the soil, reappearing as efflorescences at the surface when the rains cease and the dry air turns the direction of the movement of the solutions.*

The general occurrence of travertine about the shores of ancient lakes, notably of Lake Cahuilla; at the sink of the Carson in Nevada, and at Lake Bonneville, Utah, taken in view of the evidences of an ancient submergence of the Tucson Valley, leads to the question whether or not the caliche is a deposit from overladen calcareous waters during submergence.

*I have elsewhere directed attention to the possible enrichment of the croppings of secondary ores in mineral veins by an analogous process of concentration under desert or desiccating conditions.

It is also to be noted that the absence of caliche from the alluvial deposits tends to support the view of deposition from overlying water. Further evidence and the careful study of all the phenomena are desirable.

CHANGE OF CLIMATE.

A change of the climatic conditions throughout the Southwest, and especially in the semi-desert region of Arizona and New Mexico, is marked everywhere by the evidence of a much heavier rainfall than we now have. River valleys in many cases show only dry gravelly or sandy beds which evidently were formerly occupied by continuous streams. The floods that once carved their way across the slopes or over the plains are no longer seen, at least not in the same volume as in former time. Even existing streams do not reach in times of great flood their former volume and carrying capacity. All tell of diminished volume, whether in the desert regions or in the regions of abundant plant-growth.

We may believe that the cause is extraterrestrial and cosmic, and a part of the great era of climatic changes giving to the earth the glacial era, and its gradual decay. We may believe that the era of greatest precipitation in the Southwest and elsewhere was coincident with the widest extension of the glaciers and that while the higher mountains were being loaded with snow, the lower slopes were deluged with rain or watered freely by the melting snows and enjoyed a verdure no longer possible.

The gradual desiccation of Arizona and other regions may be regarded as synchronous with the gradual disappearance of glaciers, a condition now in progress, as shown by the retrocession of glaciers still in existence, even in the Sierra Nevada of California, where only remnants remain of the once mighty sheets of ice which covered that region.

EXTINCTION OF THE GREAT MAMMALS.

The vast extent of the ancient detrital deposits anterior to the uplift indicate a much greater rainfall than we now have, and this greater precipitation must have continued during and possibly long after the uplift, and have exerted a great influence upon the nature and distribution of vegetation.

The fact of the existence and wide geographical range in Arizona of the great mammals, the mammoth and the mastodon, shows a very different condition of vegetation up to comparatively recent geologic time. The extinction of these giant herbivores may be best explained upon the theory of the desiccation of the region rather than by a change of temperature or increasing cold, as apparently was the case in Siberia, and may have been in the glaciated regions of California. A great change in the rainfall and the drying up of the slopes and mesas of Arizona must of necessity have caused a great change in the growth of plants, involving their destruction over great areas. It would appear that the extinction of the giant mammals and the disappearance of suitable vegetation for

their sustenance proceeded together, and were due to increasing heat and dryness rather than to increasing cold.

We have ample evidence that in the Cretaceous era conditions in Arizona were favorable to forest growth and luxuriant vegetation. The coal-beds of Deer Creek near Saddle Mountain in Pinal County, described by Emerson, reveal such conditions.

Quantities of silicified tree-trunks in the vicinity of Yuma and the prostrate forms of giant trees turned to stone in the Petrified Forest Park bear eloquent testimony to such forest growths and to destructive climatic changes in Tertiary time.

More recent evidence is found in springs surrounded by relics of vegetation, such, for example, as Andrade's Spring east of Tucson and on the right bank of Davidson's Canyon, where there is a thick accumulation of sphagnum with stumps of trees and, at the bottom, teeth of the mastodon.

The former existence in Arizona of a species of *Bos* of unusual size is shown by the discovery of enormous horn-cores in the gravels of the secondary or derivative slopes of the Santa Ritas at Greaterville.

SUBMERGENCE AND ELEVATION.

In addition to other evidences of change of level of the Tucson region in comparatively recent geologic times, we have the ancient Lake Quiburis, already described, which occupied the adjoining valley on the east.

The vast accumulation in this valley of lacustrine clays and silt, now exposed to view on each side by erosion, bears good evidence of the long duration of the submergence of the valley and of the height of the water at about 4,000 feet, or nearly the height of the divide between the Tucson Valley and San Pedro, corresponding to the indications of the ancient level about Tucson. Without assigning this figure as the limit of the depression or of the total elevation of the region of the southwest, the comparatively general and uniform altitude of the detrital slopes favors the view that the sea-level rested for a long period at about that altitude.

Upon this assumption it becomes interesting to note what the form of the coast-line must have been during the period of depression, and to illustrate it the accompanying sketch-map has been prepared (plate 52).*

It presents the land areas of the southwest, including Arizona and the southern portion of California, which rise above the contour line of 4,000 feet. The areas of less altitude are represented as under water.

Without claiming absolute accuracy in delineation, the map serves to give a general idea of the coast-line before the Pliocene uplift and to help elucidate some phenomena of the geographical distribution of the plants of the area and of the probable climatic conditions in Tertiary time.

---

*This was exhibited by the author at a meeting of the Cosmos Club of Tucson, in May, 1906.

The salient features of the representation are:

1. The wide extension northward and eastward of the Gulf of California; northward up the valley of the Colorado River to and into the Grand Canyon and into Nevada; eastward to the upper Gila and the Salt River.

2. The deeply indented and rocky coast-line of Arizona, with many estuaries and bold headlands.

3. The insular condition of the region of Tucson east and west of the long valleys of the Santa Cruz, of the San Pedro and Sulphur Springs, forming a veritable archipelago in which the Santa Catalinas, the Rincons, the Santa Ritas, the Huachucas, and the Tucson Mountains formed prominent islands, while Tumamoc and other basaltic hills were under water.

4. The southern coast ranges of California disappear under water, while the southern end of the Sierra Nevada appears as a long, narrow promontory disconnected at the Canada de las Uvas from the Sierra Madre, and at San Bernardino from the San Jacinto and Peninsula Range of Mountains.

ASPECT OF THE VEGETATION ABOUT TUCSON.

The secondary maximum of precipitation in southern Arizona occurs in December and January, and amounts to 2 or 3 inches during these two months. On the higher levels this comes in the form of snow, and generally melts under the noonday sun and is almost entirely absorbed by the soil, thus yielding the greatest efficiency in promoting the growth of plants. At levels between 2,000 and 3,000 feet, vegetation begins to awaken in January and a large number of forms begin to bloom early in February, and mature fruit in March and April with the diminution of the rainfall. In all of this winter wet season, as it may be termed, the checking action is due to the low night temperatures, which drop to 30° and even 20° F. on many occasions; and a few warm days may bring a luxuriant crop of low herbaceous annuals almost to bloom, which may then be blighted by the frost in January. In the general average of such conditions it rarely occurs that the more precocious forms bloom before the first week in February (plate 53).

WINTER PERENNIALS.

A large number of shrubs and species with perennial root-stocks and bulbs push up shoots, leaves, and flowers under the stimulus of the rising temperature and the moisture supply, including the following:

Brodiæa capitata, with a few blue or white flowers borne on a slender scape with a deeply buried bulb; *Anemone sphænophylla*, a relative of the crowfoot, with long-stalked cylindrical fruits; *Penstemon wrightii*, with its crimson tubular flowers, a succession of which follow through March and April; and *P. parryi*, on the slopes, with a metallic luster to the flowers. Stalks of the last two species are a favorite food of rock-squirrels, which

Looking westward from Laboratory site. In the middle distance is shown a strictly desert vegetation, consisting of giant cactus, palo verde, ocotillo, creosote-bush, prickly-pears, chollas, etc. (Reprinted from Publication No. 6.)

cut them off near the base and carry them away to their retreats. *Hilaria mutica* is a true desert grass which finds a place high up on the slopes, where it makes patches of color visible for miles. *Cassia covesii* opens its yellow flowers and forms its pods early, while *Franseria deltoidea*, a low shrub, has its bur-like fruits ready to be carried away by any moving thing that touches them early in April. The most striking color of this period, however, is that of the globose clusters of *Encelia farinosa*, nearly a yard in diameter, which are so numerous and so dense on the slopes as to give a golden color that may be caught by the unaided eye for 7 or 8 miles. One of the wild tobaccos, *Nicotiana trigonophylla*, grows among piles of rocks or on the edge of escarpments, and its creamy yellow flowers open early in February. *Verbena ciliata* forms low clusters, and the individuals in any locality show a range of variation of color of flowers from deep pink to pure white, while the flowering season is ended only by the spring drought. The creosote-bush, *Covillea tridentata*, begins to open flowers and make new leaves in February and continues in flower for two or three months. On the mesas and sandy washes the composite *Baileya multiradiata* opens numerous yellow flowers from its clumps of stems, that last with their brilliant yellow effects for many days. Low and decumbent on the hill-slopes are the crooked branches of a small shrub, *Calliandra eriophylla*, which forms clusters of flowers of a delicate pink and soon matures its fruits, while a second species of the genus, less inconspicuous, abounds on the lower mesas.

The greater number of these perennials cast away their leaves with the approach of the high temperatures of April and May, and the stem, bulbs, or root-stocks go into a quiescent condition from which they do not awaken until the following December or January, eight or nine months later, the entire period of activity being comprised within a compass of a hundred days. Some, however, like *Covillea*, with varnished leaves, and a few other species with heavy protective coatings of cutin or hairs on the foliar surfaces retain these organs during a great part of the year, and derive some benefit from the activity of the chlorophyl during the intense insolation of the summer months. While the soil is supplied with water in fair plenty, at least during the early part of this season, the humidity of the air ranges between 30 and 40 per cent and only plants with protected surfaces may functionate to advantage in it.

WINTER ANNUALS.

Of the large number of herbaceous forms which spring from germinating seeds in the wet winter season and soon pass the whole cycle of existence, a few of the more prominent may be mentioned.

Astragalus nuttallianus, an innocuous relative of the "loco" weed, ripens its curved reddish pods early in March and scatters the seeds in the gravel, the small stems withering away long before the summer comes.

Streptanthus, one of the mustard family, soon reaches the adult stage, with its deep greenish stems and rather lush leaves, which show but little indication of belonging to the desert. Two of the borages, *Harpagonella* and *Pectocarya*, occupy the most prominent place in this group of plants, the soil being generally so thickly sown with their seeds that the rains bring up a dense carpet of these plants; every square inch of available space on Tumamoc Hill is occupied with their short hairy stems, the burs being quickly matured, and in the dry weeks of April forming an unpleasant [illegible]ture of a walk off the trail. Two plantains abound: *Plantago aristata* [illegible]ys on the slopes, while *P. ignota* is abundant over vast areas of gravelly [illegible] sandy mesa, the silvery hairy and grayish appearance of the leaves [illegible]ing such that it is difficult to determine at a glance whether the plants [illegible]re alive or dead. Of the annu[illegible]se two are furnished with the structures most generally characteristi[illegible]s that live in dry places. *Phacelia tanacetifolia*, with its scorpi[illegible]escence, is scattered among the rocks and on the slopes over a wi[illegible] ra[illegible]e, and as it does not come into [illegible]oom until well on with the con[illegible]ry weather, it and its neighbor, *Amsinckia*, with yellow flowers, have [illegible]ome of the features of desert plants. Early in April, shining silvery [illegible]alls of fruit, reminiscent of the dandelion, are met frequently, and these prove to be relatives of that weed, being *Microseris linearis*, with erec[illegible] linear leaves around the scape which bears the fruit, and *Rafineskia*, w[illegible] shorter laciniate leaves on its thicker stems. The wild carrot, *Daucus pusillus*, holds its umbels of inconspicuous flowers but a few inches above the ground, and these ripen seeds in April, when the entire plant quickly dries up. *Bowlesia lobata* is abundant in certain localities, while two gilias, relatives of the phlox of the gardens, are abundant. *Gilia floccosa* displays its small star-shaped flowers everywhere on short simple or branched stems, which, with a supply of water, take on some stature and throw out laterals, but which usually send up a single stem with a hairy globose head, from which every day a flower opens that may vary in color from pure white to deep blue. The other species, *G. bigelovii*, stays mostly on the slopes, and its slender shiny stems are taller than the species described above. Here and there are to be found small compact clusters of flowers like small white daisies borne on short stems, *Eremiastrum belliodes*, which also exhibits the marks of the desert. Finding its way about, across the mesas and over the hill-slopes, is the alfilerilla, *Erodium cicutarium*, a relative of the geranium, which spreads its flat rosettes of greenish laciniate leaves wherever it may find a foothold, and after its pinkish flowers come the long fruits, which sow the seeds so abundantly and efficiently that this plant travels by leaps and bounds. Small straight stems, clothed with hairy linear leaves, terminate in spikes of delicate purple flowers in *Orthocarpus purpurascens palmeri*, and single individuals occur here and there on the mesas, in the sand and gravel, but in some places so

densely are they crowded that great purple patches are formed on the slopes. Occasionally an individual is found which has lost entirely the power of making the characteristic color of the flowers, while others lack it only partially, and of these an experimental study has been begun. The Mexican poppy, *Eschscholtzia mexicana*, likewise offers many things of interest. Its flowers are light yellow or have a distinct admixture of red; its petals show entire margins or are deeply cut; the orange eye at the bottom of the corolla cup may be clearly defined and sharp or diffuse; but, most striking of all, a number of individuals have been found in which the foliage has a paler color than ordinary and the flowers are of a clear creamy white, the eye at the bottom being the only color retained, and at the same time the margins of the petals are delicately frilled, making a most striking deviation from the main type, between which numerous intermediates are to be found.

The more prominent structures by which these annuals are fitted for life in the desert are not to be looked for in the shoots or leaves, but in the seeds and their powers of endurance. Seeds are ripened and thrown on the ground in March and April. The surface layers of the soil reach a temperature of over 100° F. during the summer months, the summer rains come and soak both the soil and seeds, but still no activity is shown, and the experimentalist who attempts to use these plants during the summer will find that he might as well have sown so many pebbles in his pans. The summer cools into the autumn, and cooler nights come, followed by the winter rains of December; then and not until then do these refractory seeds begin to show signs of life. Two features are possibly involved in this delayed germination. One is that the seeds need a certain length of time for the carrying out of slow changes toward maturity, which take place during the so-called resting season and which need a period of determinate length not to be shortened. Secondly, it is quite possible that in some species the baking summer heats, the moist soil, the cool nights of autumn, and the rains are a series of stimuli which must follow each other in turn and act for a length of time before the seedling emerges from its protecting coats. Favor is lent to this view by the fact that in some species germination may be induced earlier by simulating the summer heats and the winter coolness by the use of the oven and the refrigerator.

SPINOSE AND SUCCULENT FORMS OF THE DRY FORESUMMER.

The precipitation shows a decrease to 0.90 of an inch during February, and this, with a further diminution to 0.77 inch during March, coupled with the steadily rising temperature, brings to an end the lush and luxuriant vegetation of the moist winter season. Late in March or early in April the xerophilous conditions come to full expression. The stimulus of the still increasing temperatures and of the decreasing relative humidity

now brings into activity the succulent, spinose and xerophytic types which especially characterize the season. This dry foresummer may be said to comprise April, May, and June, with a total average precipitation of 0.67 inch, while the maximum temperatures range from 95 to 112° F. The evaporation of course exceeds the precipitation in an enormous ratio.

The succulents comprise two general types, one of which is represented by the cacti with atrophied foliar organs and storage stems, and the other by the yuccas and agaves with the thickened leaves and short stems functioning as reservoirs for the water which was accumulated during the latter part of the winter wet season.

The greatest activity among the cacti is displayed by the cereuses and opuntias. The earliest of these in the vicinity of Tucson is generally *Echinocereus fendleri*, in which a few brilliant crimson flowers are displayed from the clumps of short, thickened, cylindrical stems late in March, and continue for a month, to be accompanied and followed by equally noticeable bloom of two or three other small species. Chief of the group, however, is the great sahuaro, the flower-buds of which develop as dense clusters on the portions of the apices of the stems most exposed to the sun, and have been seen to open on March 25. The whitish flowers each remain open but a short time and apparently are pollinated by insects. A succession of them ensues, and although practically finished during May or June, yet belated buds open at various times, one having been seen as late as the middle of November. The seedy fruits mature in great quantity in midsummer, and are much prized by the Papagoes, who make much use of them in various ways (plates 54, 55).

The prickly-pears, or opuntias with flat stems, begin to make some growth of new joints and to push out flower-buds in March, and late in that month or early in April bloom in great profusion, the fruits maturing early and dropping to the ground. Fifteen or twenty species are native to the Tucson region, but the greatest confusion prevails as to their identity. Of the various desert plants, this group has been the subject of the most inquiry as to its possible economic utilization. After a consideration of the various practical questions connected with open cattle ranges, it has been found that the best use of them for forage is made by growing or allowing to grow spinose species, from which the spines are burned when they are to be consumed by animals. This is now done with the plants growing in various places. Unarmed forms are subject to the attacks of so many animals that it is practically impossible to secure a crop without protecting fences. A few species are known in which the spines are very sparse. One of these, *Opuntia lævis*, occurs in the canyons of the Santa Catalina Mountains, but chiefly on rocks or in places inaccessible to grazing animals (plate 56).

The cylindrical opuntias include many forms with a central stem and well-developed system of branches which give them the form and impos-

Saguaro or giant cactus (*Cereus giganteus*), near mouth of Sabina Canyon, Santa Catalina Mountains. The openings in the trunk and branches lead to large sac-shaped cavities originally excavated by woodpeckers for nests, and afterwards occupied by several other species, as well as colonies of honey-bees. This specimen is about 40 feet in height. (Reprinted from Publication No. 6.)

Cereus giganteus, with vertical branches, a form occurring around the base of the Santa Catalina Mountains and to the northward.

Plate 56

Opuntia lævis, a semi-spineless prickly-pear growing in the Santa Catalina Mountains. Young plants of *Cereus giganteus* in background.

Opuntia fulgida (cholla) and *O. mamillata*, two closely related prickly-pears growing with branches in contact. Both bear numerous maturing fruits.

ing appearance of trees. These begin activity early in April, two of the earlier ones being *O. versicolor* and *O. spinosior* (tasajo), with a puzzling range of color in the flowers. Thus, some individuals will be found which have bright crimson or reddish-purple flowers and others with light red; others with yellowish-red, yellow, and greenish-yellow, the shade also being reflected by the color of the stems, so that the color of the flower may be predicted upon seeing the plant from a long distance. In some instances two colors appear to be exhibited by a single plant, but a closer examination generally shows that what appears to be one plant is in reality two, grown together at the base.

O. fulgida is characterized by the silvery, shiny appearance of the sheaths of the spines, and is locally known as "cholla," although that name properly belongs to a species native to Baja California much farther south.

Nearly related to *O. fulgida* and growing intermingled with it is *O. mamillata*, with more greenish branches, shorter and sparser spines. Both of these species have easily detachable branches, and the separated portions act as cuttings in propagation. The facility with which the joints are cast loose and attach themselves to an animal by the sharp spines makes them much to be dreaded, and it is by this means that dissemination is effected in a very efficient manner. The fruits remain attached to the branches for one or two years, or even longer, and the seeds are exceedingly slow of germination (plate 57).

Opuntia bigelovii, which is so densely clothed with short silvery spines that a pencil-point can not be thrust against the stem without pushing several aside, shows an extremely wide range over the deserts of the Southwest from Death Valley across to the mesas of Arizona and southward along the shores of the Gulf, also propagates itself by means of detached joints, and an entire colony of these plants may be seen that have come from one older central individual.

Several species of birds make their nests in the branches of the cylindrical opuntias, where they are secure from hawks and marauding animals; and many rodents of the desert drag the detached joints about their burrows, making an effectual barricade against the coyote and fox.

The agaves form their great rosettes of thickened leaves on the slopes running up from the greater mesas, and after a period of development which varies from a few to many years a central flower-stalk is sent up in the foresummer with extraordinary rapidity, growing in length as much as a foot a day and quickly forming flowers and seeds. This effort exhausts the resources and terminates the life of the individual, and the entire cycle of these "century-plants" is directed to this one effort of arriving at mature size with an accumulated food-supply that will enable them to perfect a crop of fruits and seeds. This habit makes the agaves an important source of food for the southwestern Indians, who take the

rosettes when nearly mature and after cutting away the tips of the leaves bake the central stem and attached leaf-bases for the sugary substances to be obtained, making what is known as mescal. The mescal-pits used a decade ago are numerous in the foothills of the mountains in this region, and even yet one may occasionally surprise an Indian feasting upon this prized delicacy.

The yuccas and the sotols (*Dasylirion*) form a great central stem several feet in height with a heavy plume of leaves which may live to a great age. The inflorescence in these plants arises some distance from the apex of the stem and the flowering period does not terminate the existence of the individual as in the agave. The yuccas occur at a higher level than Tucson, while the sotol (*Dasylirion wheeleri*) inhabits the rocky canyon slopes a thousand feet above, although stragglers are found nearer (plate 58). The southern slopes of the Catalinas and of other mountains in this region is also the habitat of the small agave (*A. schottii*), which has stiff spiny upright leaves less than a foot in length, and as the plants grow thickly together an ascent among them is tedious and painful. With this species is to be found also the rarer *A. treleasii*, which so far seems to be found only on the slopes of the Santa Catalina Mountains.

The yellow of the hillsides of the early part of the year due to *Encelia* has hardly faded when equally conspicuous clumps of *Riddellia* begin to show at the same level, and the globular clusters of this plant endure for many weeks. During their display the bright yellow bloom of the parkinsonias contributes to the yellow color-note. *Parkinsonia microphylla* (palo verde) and *P. torreyana* are true desert trees, having very minute leaf-blades which are cast at any time when the water-supply fails, and which use the green layers of the bark instead when the leaves are lacking (plate 59).

Two other pod-forming groups of trees are also active at this time, the acacias and the mesquites. Of acacia there are two species, one with white and the other yellow flowers, which are sweet-scented and are borne in globular clusters on the small trees. Mesquite attains its greatest growth on the alluvial bottom-lands, and it is capable of sending long roots to great depths in search of water. The delicate green of its leaves is an especial feature in contrast with the gray and yellow of the arid landscape. In April and May small racemes of whitish flowers are followed by the pods and bean-like seeds, which are such an important feature in the life of many animals and of the Indian (plate 60).

The hackberry (*Celtis*) and *Lycium* are also to be mentioned among the woody plants which bloom and mature their fruit during this season. Of the plants which grow from seed every year none are more striking than the thistle-poppy (*Argemone*), which affects sandy slopes and washes, the glistening spiny stems and leaves being of a grayish-green, a true desert color. A large number of buds are developed and one or more are

opened every evening on many branches, so that a display of pure white flowers is offered by any individual for a period of 5 or 6 weeks.

PLANTS IN THE HUMID MIDSUMMER.

The course of the temperature rises irregularly during June until, in the latter part of this month and early in July, thermometers in the shade read as high as 112° F., and the surface layer of the soil warms up to a point where a thermograph with a buried bulb gives daily records of over 100° F., with but slight cooling at night. Lying quiescent in this soil are thousands of seeds of plants which are incapable of germination in the moist season of the cooler months, and which can not sprout in a soil which contains much less than 15 per cent of moisture. Snowy piles of cumuli begin to be seen on the mountain summits early in July, and the earlier short showers are followed by longer ones which spread out over the plain in fantastic patterns, generally giving the greatest rainfall of the year during July and August. As soon as the precipitation is sufficient to bring the soil-moisture up to the critical point, millions of seedlings spring into activity, and forty-eight hours may see the entire face of the landscape changed in appearance.

SUMMER PERENNIALS.

The great barrel-cacti, which have hitherto remained practically dormant, now having become thoroughly heated up and supplied with water drawn in by the network of roots, which ramify in all directions from the bases of their thick stems, immediately underneath the surface of the soil, now begin to open a series of reddish and lemon-yellow flowers, to be followed by the formation of a crown of maturing fruits which stay in place until the middle of the following summer. The seeds of the sahuaro, which are produced in enormous quantities, are devoured by the birds before being freed from the fruits, but of the great number that reach the ground and germinate, not one in a million survives and makes the curious globular plantlet a few inches in height eventually destined to become a giant cactus. The seedlings of all the cacti form a favorite food of a large number of small animals, being juicy reservoirs of water and containing enough other material to lead to their destruction before sufficient armament has been formed for their protection.

Some plants, in the lives of which the supply of moisture is the controlling factor, start up again with the summer rains in a season much warmer than that earlier in the year in which they have previously been active. A *Cassia* must be reckoned among these, and its brownish pods opening in August make a second liberal sowing of its seeds. A low straggling shrub, the dragon's-blood (locally known as "sangre engrado," as a corruption of sangre de drago), *Jatropha*, spreads its waxy green leaves amid many other plants of a grayer, more xerophytic aspect. The greater

part of the yellowish note in the landscape is due to the masses of *Bigelov* of two species which occur in abundance over the mesas and are plentiful supplied with resinous secretions. The pods of the leguminous tree including the acacias and the mesquites, ripen during this season and off abundant food to the larger grazing animals.

SUMMER ANNUALS.

Several euphorbias spread their small dense mats of thin stems ar minute leaves on the surface of the ground, and are rich in a latex milky juice containing resins, starch, and some caoutchouc, which reputed by the Indians of various tribes to furnish an antidote for tl venom of the rattlesnake—a supposition not confirmed by experiment evidence, however. Another group of species which forms green ma on the surface is comprised within the genus *Tribulus*. Some of the cover an area of nearly a square yard with a dense mass of green con pound leaves offering a background contrasting with the bright yello and reddish colors of the flowers, which show interesting opening an closing movements. The thin yellowish, almost leafless, stems of tl parasitic *Cuscuta*, or dodder, make a rapid growth during the humi season and quickly twine round the stems and sink their haustoria dee into the bodies of many host-plants, being capable of attacking succes fully some forms with an extremely indurated bark or epidermis. Du ing all of this season the humid air, especially after the sudden rain becomes laden with the pungent odors of the creosote-bush and of tl various volatile substances produced by many of the desert forms.

THE DRY AFTER-SUMMER.

The latter part of the moist midsummer has witnessed the beginnin of growth of a number of grasses of the genera *Triodia*, *Bouteloua*, an *Aristida*, which ripen their seeds and persist as tufted bunches of dr haulms and leaves during the rainless season of October and Novembe being eagerly eaten by grazing animals. During this season an almo total cessation of vegetative activity ensues, and continues until tl double stimulation of the moisture of the winter rains and of the increa ing heat of the sun after the winter solstice is received. Then the season succession of forms ensues as described, with various modifications du to the wide departures from the normal or average conditions. An exan ple of this diversity is suggested by the records of precipitation, whic may vary from 5 to 25 inches per year.

Slope in Pima Canyon, Santa Catalina Mountains, bearing *Opuntia versicolor* and *Dasylirion wheeleri*.

Dry alluvial flat of Rillito wash. Canaigre (*Rumex hymenosepalus*) and *Ephedra* in foreground. Palo verde (*Parkinsonia microphylla*), mesquite, and saguaro in background.

Cats-claw tree (*Acacia greggii*) near Tucson, Arizona, affected by a mistletoe (*Phoradendron californicum*).
(Reprinted from Publication No. 6.)

TEMPERATURES OF PLANTS IN THE DESERT.

No exact determinations have been made of the intensity of insolation in American deserts with respect to its effect upon vegetation, but it may be assumed to be high, partly on account of the low relative humidity. The green chlorophyl screens of the shoots, whether in leaves or green stems, are subject to the direct action of the rays and take on a temperature only modified by the cooling action of transpiration, which, however, must be slight in many instances, particularly in the cacti, which have been found to throw off water more rapidly in their native habitats by night than by day. Then again the action of the sun's rays heats the surface layers of the soil, in which the roots of many species lie, so that in some cases at least the absorbing organs are embedded in a medium much warmer than the air. This point is illustrated by the following observations made near Flagstaff, Arizona, July 16, 1898:

The bulb of a mercurial thermometer was pushed down into the soil around the root tips of a clump of bunch-grass to a depth of 2 inches, and the glass stem of the instrument shaded from the direct rays. The soil consisted of a mixture of volcanic sand and alluvial deposit. At 2^h 20^m p. m. a temperature of 106° F. was recorded; a few minutes later 108° F., with the air ranging from 91.4° to 93.2° F. At 3 p. m. the black volcanic sand around the roots of *Cleome serrulata* showed a temperature of 111° F., with the air at 113° F. Professor Toumey cites the fact that the temperature of the soil at the depth of 1 inch near Tucson reaches a temperature of 113° F., with a mean average of 104.9° F. for the entire month of July; also that the average for the month of July at a depth of 4 feet was 82° F. with a maximum of 84.5° F. and a minimum of 81° F. Professor Toumey states that the temperature of the soil near Tucson increases slowly during July, is stationary during August, and begins to decrease in September. These observations are of great interest, since the insolation would be practically identical with that near Flagstaff, although the altitude of the latter place is somewhat greater. The soil in which the observations at Tucson were made consisted chiefly of decomposed granite with some mica.

Mr. A. E. Douglass, of the University of Arizona, has communicated some observations indicating that the sandy soil around the roots of small herbaceous plants in the Grand Canyon, Arizona, on September 4, 1898, exhibited temperatures as high as 148° F.

A pair of Hallock soil thermographs have been in operation at the Desert Laboratory since 1905, and it is found that these extreme temperatures are met only by the roots of species spreading in the surface layers of the soil. The records taken at 6 inches below the surface during the

last week in July, 1906, show a variation between 85° and 98° F., although it is to be said that this type of instrument responds somewhat slowly and it is quite possible that the maxima might have been as much as 3 or 4 degrees above that shown for a few minutes. When these instruments were first installed the bulb of one was placed with its center 3 inches below the surface, with the result that the tracing pen rose above the slip and temperatures of 102° and 105° F. were indicated. At a depth of a foot the temperature during the week indicated did not show a daily variation of over 2 degrees, but a continuous rise of 6 degrees occurred.

It is not to be taken for granted that all plants native to the region are active under such conditions, however. The winter annuals and perennials come to bloom early in February in great number, and it is to be seen that the roots are embedded in a soil that ranges from 48° to 55° F. at 6 inches from the surface, while at a foot the mean average is practically the same, with a narrower amplitude of diurnal variation. This temperature at the depth of a foot is practically the same as that recorded for midsummer in New York.

A study of the mechanism of absorption would doubtless detect by comparison some important differences between the roots of winter annuals which take up soil solutions at 50° F. and those of the summer flora which habitually function at a temperature in the neighborhood of 100° F., 50 degrees higher. Important correlations with the transpiratory activities may also be expected.

The temperatures of a number of plants were obtained by thrusting the bulbs of small mercurial thermometers into the fleshy stems and shading the exposed portion of the instrument from the sun's rays. The following data were recorded from tests of this character with an opuntia on July 17, 1898:

Temperature of—	$7^h 20^m$ A.M.	$8^h 10^m$ A.M.	$9^h 00^m$ A.M.	$10^h 30^m$ A.M.	$11^h 00^m$ A.M.	$11^h 30^m$ A.M.	$12^h 30^m$ P.M.
Opuntia......	79.0° F.	93.5° F.	93.8° F.	97.2° F.	111.2° F.	109.4° F.	108.0° F.
Air..........	78.5	82.4	87.8	91.4	96.8	100.4	100.4

The flattened fronds of the cactus were in an upright position, with the edges in the plane of the meridian, so that the angle of the incident rays of sunlight decreased with the altitude of the sun. As a consequence of this insolation the resulting temperatures rise until about 10 a.m., and then decrease until the sun once more comes into a position where the rays might strike the surface at or near a right angle, reaching a second maximum at 2 p.m., though observations on this point were somewhat obscured by the daily clouding at the time of the experiments.

The above data were obtained at Flagstaff, Arizona, at an altitude of about 7,000 feet, and some further measurements were made at the Desert Laboratory on April 13, 1907, on opuntias similar in form to the above and which were showing flower buds about to open. Fronds in a vertical position were selected which were facing toward the point on the horizon directly under the sun at 2 p. m., and into these were thrust the slender bulbs of thermometers the glass stems of which were shaded. Readings of 108° to 117° F. were obtained with the air at 92° F.

In the thermometry of globular, decumbent, or cylindrical forms of fleshy plants, such as *Cereus*, temperatures of 113° to 115° F. were often found with the air at a temperature of 93° to 100° F. It is to be seen that plants in this region are subject to the action of a fierce insolation and to an atmosphere of low relative humidity. As a result of such insolation the body of the plant and the surface layers of the soil are raised to very high temperatures. The increase in temperature of the shoot aided by the direct action of the light upon the transpiratory mechanism would tend to increase the amount of water given off by the shoot. At the same time, however, the temperature of the soil undergoes a corresponding increase, thereby increasing the osmotic processes of absorption, so that the two processes, absorption and transpiration, automatically equalize each other, provided the maximum temperature of protoplasmic activity is not passed.

It is not to be taken for granted that the temperatures recorded above represent the maximum limit in the matter. Algæ are found in certain springs in the Southwestern deserts which flourish at 128° F., and accredited records of air temperatures of 122° to 128° F. are available. The shoot of plants exposed to the sun under such conditions would doubtless be as warm as 135° or perhaps 140° F. It is evident therefore that the supra-maximum temperature of active protoplasm and of chlorophyl usually quoted in text-books are good for the laboratory only, and do not measure the range of endurance offered by desert forms. Capacities of this character would probably be found to depend upon the character and structure of the proteid constituents of living matter, as well as on the water content necessary for growth and for other functional and vegetative activities.

In comparison with the above, some data obtained by Messrs. Douglas and MacDougal on the summit of San Francisco Mountain, near Flagstaff, Arizona, are of interest. Observations were made at a camp at 11,500 feet during the first week in August, 1898, and some recording instruments were kept in operation for a longer period. A consultation of these records shows that the temperatures did not range so widely during the course of a day as at lower altitudes. The difference between the soil and air seems very marked, however. Kerner estimates that at an elevation of 3,000 feet the mean temperature of the soil in humid localities

is 2.7° F. greater than that of the air; at 4,000 feet it is 3° F.; at 5,000 feet, 4.3° F.; at 6,000 feet it is 5.4° F., and at 7,000 feet it is 6.5° F. In an observation made at 4 p.m. August 8, on the western slope of the peak, the soil stood at 71.6° F. and the air at 57.6° F., and at 7 a.m. the next morning the minimum of 21.2° F. was obtained for the air and 48.2° F. for the soil. This increase in the difference between the temperature of the soil and the air is due to the increase in intensity of the direct sun's rays and the diminution of the intensity of the diffused radiation by reason of the attenuation of the atmosphere at such altitudes.

No records of the temperature of living plants under such conditions are available, but it is evident that the entire subject needs reinvestigation by exact methods in which the separate effects of ground radiation and direct insolation will be separately accounted for. Such studies would be carried out in a system of observations which would embrace plantations including identical forms grown at different altitudes.

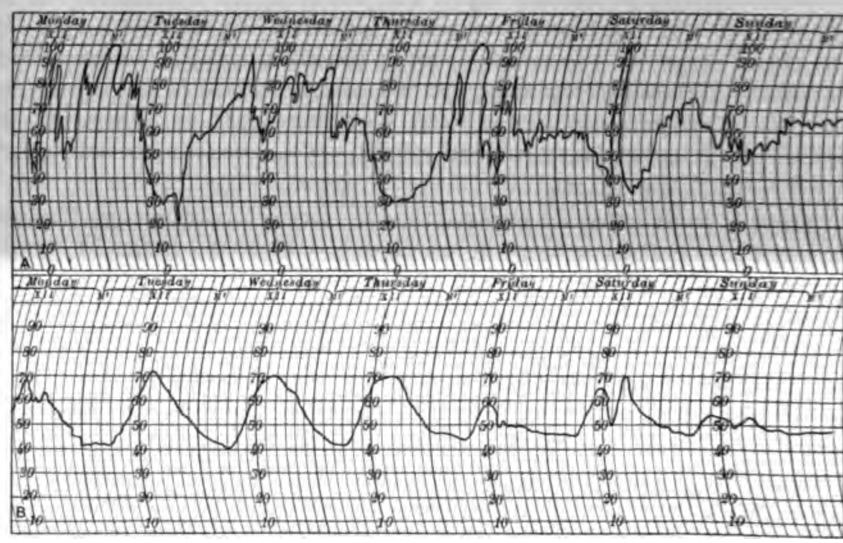


FIG. 1.—Meteorological data from San Francisco Mountain, Arizona, August 8 to August 19, 1898. The upper curve, traced from the hygroscopic record, shows variations in relative humidity. The lower curve shows the corresponding air temperature in the shade. (Reprinted from Publication No. 6.)

Some important results have already come to hand from the investigations carried on by the Committee on the Relation of Plants to Climate of the American Association for the Advancement of Science.

Dr. MacDougal, to whom the work on soil temperatures was intrusted, reported as follows on a series of observations made at a depth of 6 inches in the New York Botanical Garden (Monthly Weather Review, August, 1903):

It may be seen from these that the maximum daily temperatures occurred between 8 and 11 p. m., and the minima 12 hours later, or between 8 and 10 a. m. The optimum temperature for absorption by roots lies well above that of the soil, at the depth at which the observations were made. It follows, therefore, that the temperature of the soil approaches this optimum most nearly, and offers most favorable conditions for the taking up of watery solutions at a time of the day when the amount of water thrown off by the shoot and of mineral matter used in metabolism are nearing the minimum by reason of the absence of light, lowered air temperature, and consequent increased humidity of the air. These inharmonious conditions account almost wholly for the profusion of guttation excretions, or "dew-drops," formed on the tips and margins of grass blades and leaves of low-growing plants early in the evening.

Absorption by the root continues quite vigorously after sunset by reason of the favorable temperatures; and the augmented amount of fluid in the cortex of the roots sets up a pressure which ultimately forces the water into the central cylinder and up through the woody cells faster than it may be used and transpired by the thin-walled cells of the leaves. The vessels become filled with water which is forced out in form of drops through the excretory openings. In some species the amount of water coming away from the plant in this manner may reach quite an appreciable quantity.

On the other hand, the forenoon witnesses the rapid acceleration of transpiration by all parts of the shoot at a time when the soil temperature is decreasing to a minimum. The increase of transpiration continues until mid-afternoon, while the temperature of the soil reaches a minimum two or three hours earlier, and then begins to rise, but does not do so sufficiently to favor absorption to any great extent. It is true, of course, that the needs of the leaves may be partially met by the activity of the rootlets which lie nearer the surface.

When plants are cultivated in pots in greenhouses, the small volume of soil around the roots responds much more rapidly to changes in the temperature of the surrounding air and to the influence of streams and sprays of water than does the upper layer of soil in the open. In general, the soil in the greenhouse will show a much higher average temperature, which, with the other conditions mentioned, makes necessary special treatment on the part of the gardener. If the natural conditions of water-supply by precipitation were complied with, the needs of the plant would by no means be met under the altered conditions of temperature.

Another point of interest in the present connection is the fact that such notable differences are found between the temperatures of the subterranean and aerial portions of the bodies of plants at almost all seasons. During June, 1902, the shoots of herbaceous plants were in an atmosphere that varied between 8° C. (46.5° F.) and 34° C. (92.5° F.), while the roots were between 8° C. (46.4° F.) and 13° C. (55.4° F). As the maxima and minima were not synchronous the actual difference between the temperature of twigs and leaves on the upper part of the plant and roots on the lower amounted to as much as 22° C. (nearly 40° F.) at certain times of the day. Such conditions occur, though slightly less accentuated, during the entire summer in this locality. It is evident without further discussion that such differences in the temperature conditions of the two poles of the plant must exert a more or less important influence on the transport of fluids and solutions from one part of the plant to another. Referring to

the previous discussion concerning the comparative transpiration and absorption during the day, it is to be seen that the heightened temperature of the shoot must operate, in a simple physical way, to greatly augment the amount of water thrown off, while the roots must take water at the same time to meet the loss, at a temperature as much as 40° F. lower.

During the movement of the water from the roots to the leaves of grasses and other low-growing plants a total distance of no more than 50 centimeters (20 inches) may be traversed, occupying a matter of a few minutes or an hour at most, during which time the temperature is raised the above amount. The warming of the liquid as it passes upward through the living and non-living cells is attended by alterations in its solubility of mineral and organic substances and by a decreased capacity for holding gases in solution. The downward movement of solutions of sugars, acids, and nitrogenous substances from the leaves encounters the opposite set of conditions. This movement takes place almost entirely by osmose and diffusion, and is a much more complicated process, both chemically and physically, taking place in living cells only. The cooling of the liquid would entail alterations in its power of carrying substances in solution, and would also alter its physical relations to atmospheric gases.

It may be said, in conclusion, that the facts disclosed as to the actual temperatures in the soil, the diurnal and seasonal change therein, lead to the belief that the differences in temperature of the aerial and underground portions of plants can not fail to be of very great importance in the physical and chemical processes upon which growth, cell-division, nutrition, and propagation depend. The determination of the effect of differences in temperature between the roots and aerial shoots has received but little consideration from the physiologist and the geographer. A careful analysis of the conditions and results of experimental observations, carried on with plants under artificial conditions with the roots and shoots under abnormally similar temperatures, would no doubt result in the detection of many mistaken conclusions, especially in regard to absorption, translocation, and transpiration.

That soil temperatures and their relation to those of the air must be of very great importance in the cultivation of economic plants is self-evident, especially in species in which the desired useful portion is formed underground and receives storage material formed by the activity of the aerial organs. Thus, in the case of such plants as the potato, certain mineral substances are absorbed from the soil at a comparatively low temperature, carried aloft into the heated leaves, where they participate in activities resulting in the formation of sugars, starches, and other carbohydrates, perhaps some nitrogenous substances as well, and then these complex bodies are slowly diffused downward, with many accompanying chemical and physical modifications, to underground cool-storage organs, where a condensation occurs and the products are stored in insoluble form in the tuber.

THE WATER RELATIONS OF DESERT PLANTS.

During recent years it has become increasingly apparent that data obtained by the measurement of the activities of plants under laboratory conditions are oftentimes misleading, especially when dealing with forms fitted for special conditions, as illustrated by the water relations of desert plants. One of the earliest series of experiments in the field to remedy this defect was carried on at Turkey Tanks, on the western edge of the Malpais Desert, near the Little Colorado River, east of Flagstaff, Arizona, at an elevation of 6,500 feet, in July, 1898. Attention was given to transpiration and temperatures and the results are given below.

Measurements of transpiration were made by means of a potometer of the form described in the *Botanical Gazette* (vol. 24, 110, 1897). This apparatus consists of a long calibrated tube of small internal diameter supported in a horizontal position and fitted with a Y extension at one end. The tube is filled with water and the excised shoot of a plant fitted to one end of the Y by means of a tightly wired section of rubber tubing. The other end of the Y is closed by a stopcock, which may be opened to admit water when necessary. The rate at which water is taken into the shoot is noted by the progress of an air bubble in the horizontal portion of the tube. It is to be borne in mind that the rate at which water may be absorbed by the basal portion of an excised shoot in contact with water may not, and probably does not, represent the exact rate at which transpiration actually takes place, but it offers a very valuable method of comparison of the capacities of shoots of various types to take up and throw off water under similar conditions.

Experiment 1.—Mentzelia pumila is a representative of a class of plants which, annually growing from seeds, produce flowers and seed during the season of greatest humidity, and then die, the species surviving through the resting season in the form of seeds. It is a marked example of the xerophytic species which have a weakly developed root-system consisting of a number of thin branching fibrous roots which extend chiefly laterally through the upper layers of soil and do not penetrate beyond a depth of a few inches. The aerial shoot has a roughened cylindrical stem about 16 inches long and a number of lateral branches of equal length, giving the entire leafy shoot a globoid form, a form characteristic of many desert plants. The specimen used was furnished with 18 branches and bore about 900 irregular narrow roughened leaves and 200 yellow flowers. The entire surface of the portion of the plant exposed to the air might be estimated at about 800 square inches. The plant was taken from the soil after the above facts had been ascertained, and the root-system was cut away from the base of the stem before attachment to the potometer as above. Several minutes were allowed to elapse before observations were taken to allow the plant to recover from the shock of handling, to which it had been subjected.

At the beginning of the experiment the apparatus stood in the shade of a small pinyon tree with a fitful movement of the air at a temperature of 80° F. During the first few minutes of the observations in which equalization of the negative pressure was in progress, the time in which a unit (100 milligrams) of water was taken up was as follows: 40, 45, 42, 48, 47, 50, 50, 50, 50, 50, 50 seconds, or at the rate of 2 to 2.5 milligrams per second. Half an hour later, at 10^h 30^m a.m., after the negative pressure had been equalized tests were made in the open, with the sky clouded, and the air at a temperature of 84° F. The periods in which 100 milligrams were absorbed were 75, 70, 80, 85, 85, 90, and 95 seconds, giving a rate of 1.05 to 1.4 milligrams per second. With continued cloudiness and the air at a temperature of 88° F. beginning at 10^h 50^m a. m., the periods were 75, 75, 60, 70, 70, 75 seconds or at a rate of 1.3 to 1.4 milligrams per second. The sun emerging from the clouds the readings of 400 milligrams in 150 seconds, 400 milligrams in 210 seconds, and 300 milligrams in 150 seconds were taken, giving an average rate of 1.9 to 2.2 milligrams per second. With the return of the clouds immediately afterward the readings were 400 milligrams in 210 seconds, 500 milligrams in 330 seconds, 900 milligrams in 600 seconds, or an average rate of 1.9 milligrams per second, decreasing to 1.5 per second as the effects of the cloudiness were felt. The rate again rose to 1.8 and 1.9 milligrams per second as the sun emerged from the clouds.

Experiment 2.—*Artemisia* sp. was used in this test. It is a low, densely branching shrub with an extensive root-system of the deeply penetrating type. It stands nearly inactive throughout the dry season, taking on a quickened growth, as demonstrated by the formation of new shoots and reproductive organs within a month after the beginning of the July rains.

A main branch with 30 branchlets, about 12 inches long, was fastened to the potometer at 9 a.m., July 16, with the air temperature 75° F. Readings of 700 milligrams in 17 minutes, 400 milligrams in 10 minutes were made with the sun obscured by clouds. In sunshine readings of 1,100 milligrams in 25 minutes, 900 in 19 minutes, 500 in 12 minutes, and 500 in 16 minutes were made, with an average of 0.6 to 0.7 milligram per second. The total area of the surface of the branch and leaves was about 960 square inches.

As a means of comparison similar tests were made with the same piece of apparatus on moisture-loving plants in the physiological laboratory at the University of Minnesota.

Experiment 3.—A well-grown shoot of the tomato with a total surface of 256 square inches was fastened to the potometer in a room in diffuse light with a humidity of 25 to 35 per cent, about the same as in the previous experiments, at a temperature of 79° F. Readings of 1,000 milligrams in 32 minutes and 600 milligrams in 21.2 minutes were made, giving an average rate of about 0.5 milligram per second, and subsequent

observations showed no important deviation from this rate. It is to be noted that the conditions differed from those of the desert plant in the lower temperature and the much lower intensity of the light.

Experiment 4.—*Eucalyptus globulus* was used, being the shoot of a young plant grown from seed in the greenhouse and having a surface of 352 square inches. The test was made at the same time of day (10 to 11 a. m.), and under approximately the same conditions as experiment 3. Readings of 500 milligrams in 7.5 minutes, 9.5 minutes, 10.5 minutes, 10 minutes, and 10 minutes were made with an average rate of 0.79 to 1.11 milligrams per second.

The data furnished by the above tests afford a fair means of comparison of the relations of moisture-loving and desert plants to water if due allowance is made for dissimilar conditions. It is to be seen that a given area of surface of *Mentzelia* at similar temperatures and in a light vastly more intense and in a drier atmosphere transpires water at a rate slightly less than the tomato and at a rate about a third to a half that of *Eucalyptus*. The exposure of the two last-named species to similar temperatures, insolation, and dryness of the air would doubtless show that the moisture-loving plants would take up and lose water at a much greater rate.

The shrubby *Artemisia* was found to use water at a rate per area about one-fourth that of the tomato under the dissimilar conditions offered. An increase of the temperature, insolation, and dryness of the air affecting the tomato would doubtless increase the ratio many times.

Still another interesting suggestion arises from these results. *Mentzelia* is an annual that carries on its growth only during the season of maximum humidity, while *Artemisia* is an example of the perennial shrubby plant which makes no reduction of its surfaces during the dry seasons. The latter therefore must be better protected against the danger of drought and actually uses only about half the amount of water per area of surface that is needed by *Mentzelia*, and it sends its roots to enormous depths to insure a constant supply to keep up a steady but slow rate of transpiration.

The fleshy cacti are examples of wholly different types of shoots, in which the leaf-organs are reduced to a minimum. Dr. W. A. Cannon has found that a young sahuaro (*Cereus giganteus*) about 4 inches high and of cylindrical form transpired 33 milligrams of water per hour in an atmosphere with a relative humidity of 32.5 to 35.5, while a bisnaga (*Echinocactus wislizeni*) of the same height, but globular form, and hence great surface, gave off but 9.6 milligrams per hour in an atmosphere with a relative humidity of 35 to 45 per cent. It is quite possible that the specific rates correspond to the different types of root-systems with which these two forms are equipped. These fleshy forms, however, have such storage capacity that the rate of water loss does not have a direct con-

nection with the amount available in the soil. Thus it was found that a small plant of *Opuntia versicolor* gave off water at a rate of 129 milligrams per hour in April, 27.5 milligrams in June, and 26.1 milligrams in July, after the ground around the roots had been thoroughly wetted. A renewal of growth following the summer rains brought about an acceleration, due in part to the activity of the minute leaves, which are highly functional in transpiration.

It is not to be taken for granted that the measurements given above represent absolute capacities, for not only is the rate of transpiration affected by a wide variety of conditions, but also a great individual diversity results from environmental differences. Prof. V. M. Spalding (Biological Relations of Certain Desert Shrubs, *Botanical Gazette*, vol. 38, p. 122) found that a plant of *Covillea* grown with a plentiful supply gave off water 3.7 times as rapidly as one reared under more arid conditions.

The facts brought to light by Dr. W. A. Cannon (On the Water Conducting Systems of Some Desert Plants, *Botanical Gazette*, vol. 39, p. 397, 1905) also show a lack of correlation between the amount of development of conducting tissue in stems in general, and the water-supply. It does seem probable, however, that this development is influenced largely by the water-supply available at the exact time when the conductive cells are in a formative condition.

In all of these investigations it was found possible to make use of a method of measuring transpiration available in dry climates, in which the test-plant was inclosed in a bell-jar of known capacity and the amount of water thrown off estimated from the changes in relative humidity indicated by a hair hygrometer inclosed with the plant. In test-periods of a few minutes nothing superior to this method has been found.

Further work upon the subject by Professor Lloyd has demonstrated that the rate of transpiration exhibits no close relation with the movements of stomata, and that these minute organs have but little of the adaptive capacity with which they have heretofore been accredited. In fact it is found that the variations in the daily rate of transpiration are capable of rational interpretation only by the strictest comparison with the conditions of relative humidity and when taken, as described by Dr. B. E. Livingston, as relative transpiration (Relation of Desert Plants to Soil Moisture, Carnegie Institution of Washington Publication No. 50, 1906), governed largely by purely physical factors, although subject to physiological regulation the mechanism of which is not understood. Thus it was found that this regulatory action was exerted to check water-loss at temperatures between 79° and 90° F. in the plants examined, and that checking action disappeared at temperatures ranging from 80° down to 75° F.

With regard to any possible capacity of desert shrubs to absorb moisture from the air during periods of high relative humidity, the inves-

tigations of Spalding (Biological Relations of Desert Shrubs, *Botanical Gazette*, 1906, vol. 41, p. 262) show that xerophytic types are the more unfitted for this purpose the more widely do they differ from those inhabiting moister regions. The chief specializations, then, of the plants of the desert are concerned with soil moisture, checks on loss of water, and the development of storage organs which would conserve a surplus accumulated during a period of much precipitation.

SOIL RELATIONS OF DESERT PLANTS.

The soils of deserts naturally present a wide range of physical character and chemical composition. In regard to the latter feature it is to be pointed out that such soils offer a small proportion of organic matter or humus, and that in many places certain saline compounds and alkaline salts are present in the surface layers, owing to defective drainage or lack of the leaching effect of precipitation. In such highly charged soils the specially adapted halophytic forms also characteristic of sea-beaches find a foothold.

In all other soils in which clay, loam, sand, or rocks predominate the feature which has the greatest determining influence is that of the amount and disposition of the moisture. Many striking dispositions of the root-systems are being discovered which can only be correlated with the moisture factor.

Water being so conspicuously lacking on the surface of a desert, the opinion finds favor that the roots of plants established there must have enormous penetration and reach down to a supposititious supply of water far below the surface. If such were the case these organs would in some instances need to penetrate several hundred feet, because after a depth of a few inches is reached the amount present does not increase very rapidly. Deeply penetrating roots are found for the most part in shrubs growing in loam or alluvium in bolsons or valleys where a supply of water is to be found within a reasonable distance of the surface, and the increasing amount coming with depth must act as a stimulating factor both in the growth and directive action of the plant. Thus Coville reports an observation of a main root of a *Prosopis juliflora* near the streamway of the Amargosa River in California which had a length of about 50 feet. A similar exaggerated vertical development is to be remarked especially in the seedlings of species inhabiting localities in which the supply of moisture lies deep. The date-palm makes an initial root of great length, as well as *Welwitschia* and numerous other forms.

In the analysis of the meaning of any root-system it must be borne in mind that these organs have a dual function—that of anchorage and of absorption—while in some instances storage facilities are afforded both for water and for food material or surplus starch or sugar.

A marked feature of the distribution of desert forms is the peculiarly isolated position of the separate individuals, especially in the perennials. Each shrub will occupy, to the exclusion of others of its kind, an area of many square feet or square yards. With this wide separation one is quite prepared to find a great horizontal distribution of the roots, and this does occur in many species, but is not to be taken for granted in any instance not confirmed by actual observation. Long lateral roots of *Yucca* have been recorded on page 11 of this paper and on many other species, but the character is wholly a specific one. Dr. W. A. Cannon has found that distinct types of root-systems exist among species inhabiting the arid areas in which a marked increase in the proportion of soil moisture does not occur until a great depth is reached.

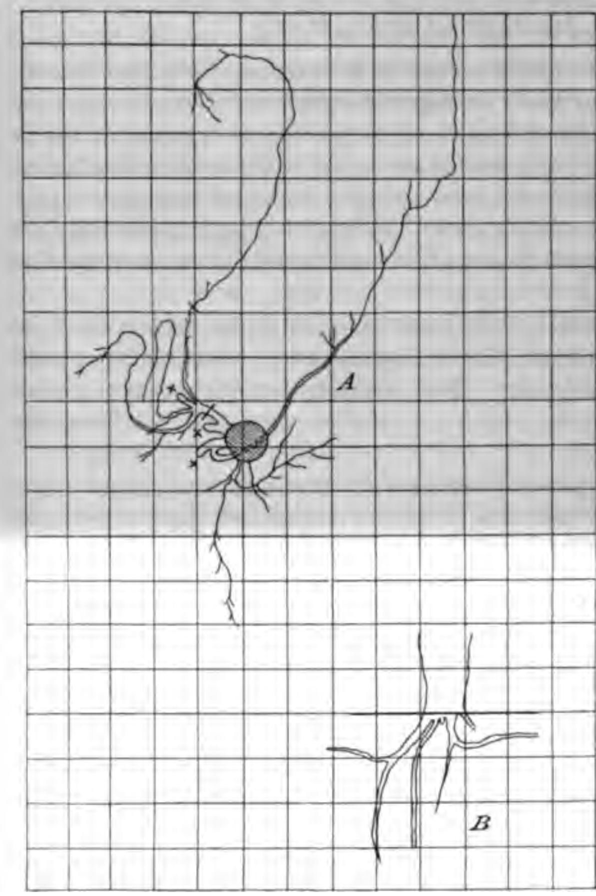


Fig. 2.—Root-system of *Cereus giganteus*. Scale: 1 unit = 4 inches.

The root-system of a specimen of *Echinocactus wislizeni* which was 60 cm. high and 35 cm. in diameter, growing about 75 meters north of the laboratory, was carefully exposed and the course of its roots mapped (fig. 3). The roots, as the figure indicates, were branched very freely. There were three main roots which arose from the base of the plant not far from 10 cm. from the surface of the ground, and which so directed their growth, and that of the branches, that the area compassed by them was about equally apportioned and well covered. As a rule, the roots were slender. At a distance of 15 cm. from the plant one of the largest of them was 7.6 mm. in diameter, and 1 meter from the plant it was 4.6 mm. in diameter. The roots ran about 6 cm. below the surface, in places which were free of stones, but when a stone was encountered the root dipped beneath it and availed itself of the better water-supply to be found there. The most deeply placed root, however, was

not more than 10 cm. below the surface of the ground. There are therefore two noticeable characteristics of the root-system of *Echinocactus wislizeni*, namely, the roots are slender throughout their entire course and they are superficially placed.

The roots of *Cereus giganteus*, on the other hand, in form and position, and perhaps in extent and branching also, are very different from those of *Echinocactus*. Fig. 2 presents the root-system of a *Cereus giganteus*, about 1 meter high, which was growing 200 meters west of the *Echinocactus* just described. Four main roots were observed to arise from the base of the plant. Very soon after leaving the plant the roots branched. One branch, whose later history could not be traced, struck directly downward, and the other took a more or less horizontal course. The latter branched at intervals, although perhaps not so frequently as those of *Echinocactus*, and extended, in one instance at least, over 1 meter from the plant's base. How much farther the root reached could not be learned because of its fragility and the small size of the distal branches. The superficial portion of the root-system of *Cereus giganteus* was more deeply placed than were the roots of *Echinocactus*, and, owing to the fact that these parts were not so densely branched, the ground included by them was not so thoroughly occupied. However, in one characteristic which is of interest to note, but the significance of which I have not investigated, the superficial roots of the two forms are alike, namely, the longer roots and the greatest number of roots are situated on the uphill side of the respective plants. This peculiarity is shown in the two figures. In fig. 3 the uphill side is to the right, and in fig. 2 it is at the top of the sketch.

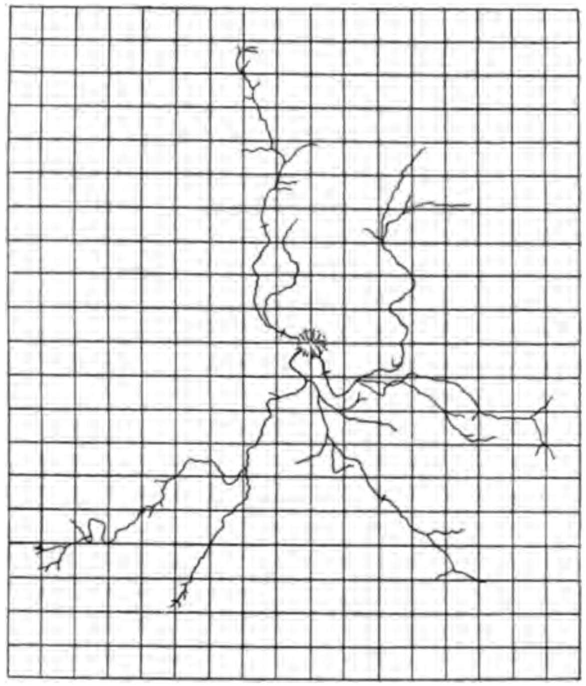


FIG. 3.—Root-system of *Echinocactus wislizeni*. Scale: 1 unit = 1 foot.

It is to be seen of course that the various types of roots also present the additional feature of varying temperature relations between the

absorbing organs and the foliar or transpiratory surfaces. Roots like those of the *Echinocactus* or of the small annuals must be exposed to temperatures identical with or differing but little from those of the shoot. Deeply penetrating roots, on the other hand, may often have a temperature as much as 40° or even 60° F. from the shoots to which the stream of soil solution is sent.

In consequence of the great excess of possible evaporation over the precipitation in desert regions, the amount and condition of the moisture in the soil must be largely dependent upon the physical properties of the principal soil constituents and of the underlying geological formation. This excessive evaporation may in itself become a factor in the laying down and structure of strata near the surface, and also indirectly of formations at considerable depth. Chief among these is the "caliche" of Southwestern deserts, which is probably duplicated in the lime deposits of the deserts of southern Africa and of other parts of the world. The evaporating power of the exceedingly dry air of the desert removes the moisture from the surface layers of the soil much more rapidly than it may be supplied by movement through the films surrounding the soil particles from below; consequently the surface layers soon become "air-dry" and the hypothetical capillary columns end beneath, retreating to a depth where the evaporation hindered by the blanket of dry soil above is balanced by the supply. Such an equilibrium is generally attained at a depth less than a yard beneath the surface. The slowly moving but constant stream of water charged with lime therefore evaporates and necessarily leaves its lime content at this depth, and in the course of centuries a "caliche" formation of considerable thickness may be formed; this in itself is a factor of great influence upon the habits of the plants which root in the soil above it.

Recently methods have been developed for the intensification of the action of the air-dry layers by pulverizing it in such manner as to form a dust mulch in what is known as "dry-land farming." The retarding effect of a dry surface layer is well illustrated in the gypsum sands in New Mexico. The action of the sun heats and dries the surface of the dunes to a snowy whiteness, and this dry layer has a thickness of a few inches only. It may be removed readily and layers moist and cool to the hand uncovered in the most arid season. By reason of this supply such plants as poplars, which are able to endure the highly charged soil solutions, but which require fairly abundant moisture, grow readily.

The air-dry layer is in part responsible for the long periods of dormancy of the bulbs, tubers, and seeds of many desert species. Such structures with the protoplasm in a resting condition, protected by heavy outer cellulose coats, may lie inert for indefinite periods in the loose layers of the dust blanket of arid regions.

CONDITIONS CONTRIBUTORY TO DESERTS.

The term desert may be applied to areas of the earth's surface which support a sparse vegetation of a more or less specialized character, owing to inadequate rainfall, or to the unsuitable composition of the soil, while the two may be present in such combination that limited areas may be devoid of any but possibly microscopic forms of plants. Of these factors scanty water-supply may be regarded as of the greatest importance, and it is to this that most deserts owe their existence. The essential and resultant features include undeveloped drainage, activity of wind erosion, great diurnal variation in temperatures, low relative humidity, and nearly humus-free soils, with comparatively small vertical increase in the proportion of soil moisture. Landscapes of this character are readily recognizable by the xerophytic aspect of the vegetation inhabiting them.

Desert conditions come about in any region in which the rainfall is markedly less than the amount of water that might evaporate from a free water surface in the open air. As the amount of evaporation increases from the poles toward the tropics and is affected by winds, it follows that no arbitrarily fixed amount of rainfall may be designated as an invariable cause of aridity. Thus in certain portions of the tropics a rainfall of less than 70 inches results in aridity, while some of the most fertile agricultural districts in the north and south temperate zones receive scarcely one-third this amount.

Regions in which precipitation is less than evaporation are characterized by a lack of running streams, or of a permanent run-off, although in some instances these districts may be traversed by large rivers which have their sources in distant mountain ranges, as in the case of the Nile in Africa and of the Colorado River in America. The rainfall in a desert may be so heavy at certain seasons as to produce torrents of great volume, which, rushing downward over the slopes and mountain sides, wear distinct streamways extending out into the plains below in some instances for miles; but the flow soon ceases after the rains have passed and the stream-beds become dusty channels until the next rainy season. Striking examples of such streamways are to be seen in the great Sonoran Desert in northwestern Mexico. It is evident that districts in which the average rainfall is not much greater than the evaporation are in a very critical condition, since in seasons of minimum precipitation the amount of water received may be less than that lost, and drought may result, often with direful effects on agricultural operations and economic conditions in general.

The seasonal distribution of the rainfall is a matter of importance in regions where evaporation is nearly as great as precipitation. If the rainfall occurs within a brief period the remainder of the year must be extremely dry and the region will show distinct desert conditions, with

a tendency on the part of the native plants to develop marked storage capacity for water. The distribution of the scanty rainfall throughout the year in any region will favor the development of slowly growing xerophytic forms.

METEOROLOGY.

The principal features in the distribution and total amount of rainfall in several localities which may be included within the arid regions of North America are given below. The data concerning the maximum and minimum temperatures and rate of evaporation afford a means of estimating the actual usefulness or availability of water-supply for the native vegetation. Thus, for example, evaporation is so great and humidity of the air so small, in the southernmost stations given, that the effectiveness of the rainfall in meeting the needs of plants is diminished 50 or even 60 per cent. Of the localities named below, El Paso, Fort Wingate, Chihuahua, and San Luis Potosi may be included in the Chihuahuan Desert, and the other places within the Nevada-Sonoran Desert.

METEOROLOGICAL TABLE.

The following tables give the mean rainfall and the absolute maximum and minimum temperatures for 16 stations, 13 in the United States and 3 in Mexico. All data for the United States stations are from records in the U. S. Weather Bureau. Data for two Mexican stations, San Luis Potosi and Chihuahua, are taken from the Monthly Bulletin of the Central Meteorological Bureau of Mexico for 1901. The rainfall record for Torres, Sonora, Mexico, was courteously furnished by Mr. T. Oldendorff, agent of the Sonora Railway at that point. The figures for this station were copied from the report made daily to the manager of the railway.

	El Paso, Texas.			San Luis Potosi, Mexico.			Chihuahua, Mexico.			Fort Wingate, New Mexico.		
	Max. temp.	Min. temp.	Mean rain-fall.	Max. temp.	Min. temp.	Mean rain-fall.	Max. temp.	Min. temp.	Mean rain-fall.	Max. temp.	Min. temp.	Mean rain-fall.
No. of years' observations.	23	23	18	1	1	1	1	1	1	5	5	39
	°	°	Ins.	°	°	Ins.	°	°	Ins.	°	°	Ins.
January.......	77	5	0.53	73	38	0.57	64	28	0.00	68	−10	1.06
February......	82	5	.42	79	38	.02	69	33	.17	69	−3	1.49
March.........	89	21	.40	79	42	.97	72	37	.02	78	5	.95
April..........	98	29	.15	90	46	.00	80	39	.05	82	19	.79
May..........	105	40	.49	91	50	.46	82	56	.46	92	11	.57
June..........	113	49	.39	91	58	.08	86	62	.58	100	29	.57
July..........	112	56	2.08	91	47	.94	..	..	4.50	99	39	2.29
August........	110	52	1.80	90	43	1.64	86	68	.84	96	42	2.15
September.....	104	42	1.11	82	56	.94	84	54	1.95	92	32	1.26
October.......	94	28	.92	79	50	.15	84	55	2.29	84	15	1.08
November.....	85	11	.50	71	40	1.44	81	31	.00	81	8	.79
December	76	−5	.54	..	37	3.20	..	..	.00	69	0	1.00
Year......	113	−5	9.33	91	37	10.41	..	..	10.86	102*	−16*	14.00

	Hawthorne, Nevada.			Winnemucca, Nevada.			St. George, Utah.			Fort Duchesne, Utah.		
	Max. temp.	Min. temp.	Mean rain-fall.	Max. temp.	Min. temp.	Mean rain-fall.	Max. temp.	Min. temp.	Mean rain-fall.	Max. temp.	Min. temp.	Mean rain-fall.
No. of years' observations.	5	5	14	23	23	22	5	5	22	5	5	15
	°	°	Ins.	°	°	Ins.	°	°	Ins.	°	°	Ins.
January.......	62	−6	0.59	57	−28	1.09	70	−1	0.98	52	−34	0.38
February......	68	6	.40	69	−22	0.88	79	1	.92	60	−21	.47
March.........	75	14	.35	82	−3	0.92	86	12	.53	75	0	.65
April..........	81	19	.20	83	12	0.85	98	18	.35	85	12	.65
May..........	85	31	.45	96	17	1.03	97	20	.36	91	25	.66
June..........	100	40	.29	98	29	.65	114	36	.06	101	33	.18
July..........	101	26	.27	104	35	.17	115	41	.44	104	34	.50
August........	100	46	.45	102	26	.16	110	43	.65	101	34	.57
September.....	95	30	.23	94	16	.35	103	31	.42	94	17	.99
October.......	80	25	.31	87	10	.56	93	20	.39	84	13	.61
November	78	19	.39	93	−9	.67	81	13	.40	70	1	.25
December......	68	0	.57	65	−20	.98	71	1	.96	52	−19	.58
Year......	101	−6	4.50	104	−28	8.31	115	−1	6.46	104	−34	6.49

*15 years' observations.

	Fort Yuma, Ariz.			Phœnix, Ariz.			Tucson, Ariz.			Mohave, Cal.		
	Max. temp.	Min. temp.	Mean rain-fall.	Max. temp.	Min. temp.	Mean rain-fall.	Max. temp.	Min. temp.	Mean rain-fall.	Max. temp.	Min. temp.	Mean rain-fall.
No. of years' observations.	26	26	20	17	17	22	6	6	15	5	5	26
	°	°	*Ins.*	°	°	*Ins.*	°	°	*Ins.*	°	°	*Ins.*
January.......	81	22	0.42	87	12	0.80	80	17	0.79	70	16	0.95
February......	91	25	.51	92	19	.70	83	17	.90	78	20	.92
March.........	100	31	.26	97	24	.58	92	22	.77	83	26	.75
April..........	107	38	.07	105	30	.30	95	28	.27	100	35	.17
May...........	112	44	.04	113	35	.13	102	32	.14	102	38	.03
June...........	117	52	T	119	33	.10	112	48	.26	107	48	.05
July...........	118	61	.14	116	46	1.03	108	59	2.40	115	64	.08
August.........	115	60	.35	116	49	.88	109	57	2.60	112	57	.04
September.....	113	50	.15	114	39	.64	107	49	1.16	104	45	.07
October........	108	41	.28	105	34	.37	98	29	.64	93	40	.25
November.....	92	31	.29	97	24	.54	90	21	.81	84	27	.40
December......	83	24	.46	95	18	.86	83	10	1.00	70	15	1.26
Year......	118	22	2.84*	119	12	6.93	112	10	11.74	115	15	4.97

	Prineville, Oreg.			Lost River, Idaho.			Laramie, Wyo.			Torres, Mex.	
	Max. temp.	Min. temp.	Mean rain-fall.	Max. temp.	Min. temp.	Mean rain-fall.	Max. temp.	Min. temp.	Mean rain-fall.	Rain-fall, 1901.	Rain-fall, 1902.
No. of years' observations.	6	6	6	5	5	5	5	5	13		
	°	°	*Ins.*	°	°	*Ins.*	°	°	*Ins.*	*Ins.*	*Ins.*
January.......	76	− 9	0.64	45	−26	1.12	52	−23	0.23	...	0.00
February......	73	−17	1.09	49	−41	.26	54	−40	.35	...	.00
March.........	83	5	.81	62	− 1	.91	63	−14	.91	...	.00
April..........	92	12	.64	76	14	.35	74	−10	1.19	...	.00
May...........	96	21	.80	90	15	1.27	78	18	1.41	...	.00
June...........	98	24	.77	95	23	.68	91	28	1.12	...	.00
July...........	119	29	.03	99	30	.61	92	33	1.30	3.99	7.26
August........	111	30	.64	95	25	.64	91	32	1.09	1.31	3.01
September....	98	20	.81	89	21	.44	85	17	.73	.75	4.66
October.......	89	20	.75	75	14	.63	72	7	.86	.21	.04
November.....	82	9	1.06	60	− 8	.92	63	−12	.25	...	.77
December.....	76	− 5	.97	48	−23	.82	52	−27	.37	...	1.02
Year.....	119	−17	9.01	99	−41	8.65	92	−40	9.81	....	16.74

*26 years' observations.

The ratio of rainfall to evaporation can not be exactly determined, as data for evaporation are meager or wholly lacking. It has been deemed worth while, nevertheless, to get an approximate notion of this ratio by estimating the evaporation and dividing by the normal rainfall. In the following table this has been done and the results appear in the last column, headed Ratio. This table also shows the maximum and minimum annual precipitation at each station during the observation period shown in column 2.

Place.	Annual precipitation.				Annual evaporation. (estim.)	Ratio.
	No. of years.	Max.	Min.	Mean.		
		Ins.	*Ins.*	*Ins.*	*Ins.*	
El Paso	24	18.30	2.22	9.23	80	8.7
San Luis Potosi	1	.....	....	10.41	...	....
Chihuahua	1	.....	....	10.86	...	....
Fort Wingate	39	25.00	6.37	14.00	80	5.7
Fort Yuma	26	5.86	0.60	2.84	100	35.2
Phœnix	18	12.83	3.77	7.06	90	12.7
Tucson	25	18.37	5.26	11.74*	90	7.7
Mohave	26	21.38	2.20	4.97	95	19.1
Hawthorne	14	8.35	1.89	4.50	80	17.5
Winnemucca	22	11.91	4.89	8.51	80	9.6
St. George	13	9.81	3.55	6.46†	90	13.9
Fort Duchesne	15	11.43	4.36	6.49	75	11.6
Prineville	6	11.64	7.49	9.01	70	7.8
Lost River	7	11.86	6.22	8.47	70	8.3
Laramie	13	31.42	5.56	9.81	70	7.1
Torres	1	.....	....	16.97	100	6.0

*From 15 years' observation. †From 22 years' observation.

Discussion.—The foregoing meteorological data are given concerning localities which very clearly lie within the true desert regions of North America. It would be impossible to outline the included areas upon a map except by means of data obtained by an accurate and extended hydrographic and biological survey. The rate of evaporation for the several localities mentioned is roughly estimated from data taken from the Report on the Climate of Arizona by Greely and Glassford in 1891. It is probable that actual measurements might show a variation of 15 per cent by way of error in these estimates, the evaporation being over-estimated, but the ratios found may be regarded as fairly approximate for the regions in which the several stations are located. It is to be seen that the evaporation at Tucson, Arizona, and at Laramie, Wyoming,

is about 7 times as great as the normal precipitation, while at Yuma, Arizona, it is more than 35 times as great as the average or normal amount of precipitation. The evaporation at the last-named locality amounted to 160 times as much as the precipitation in the year 1899.

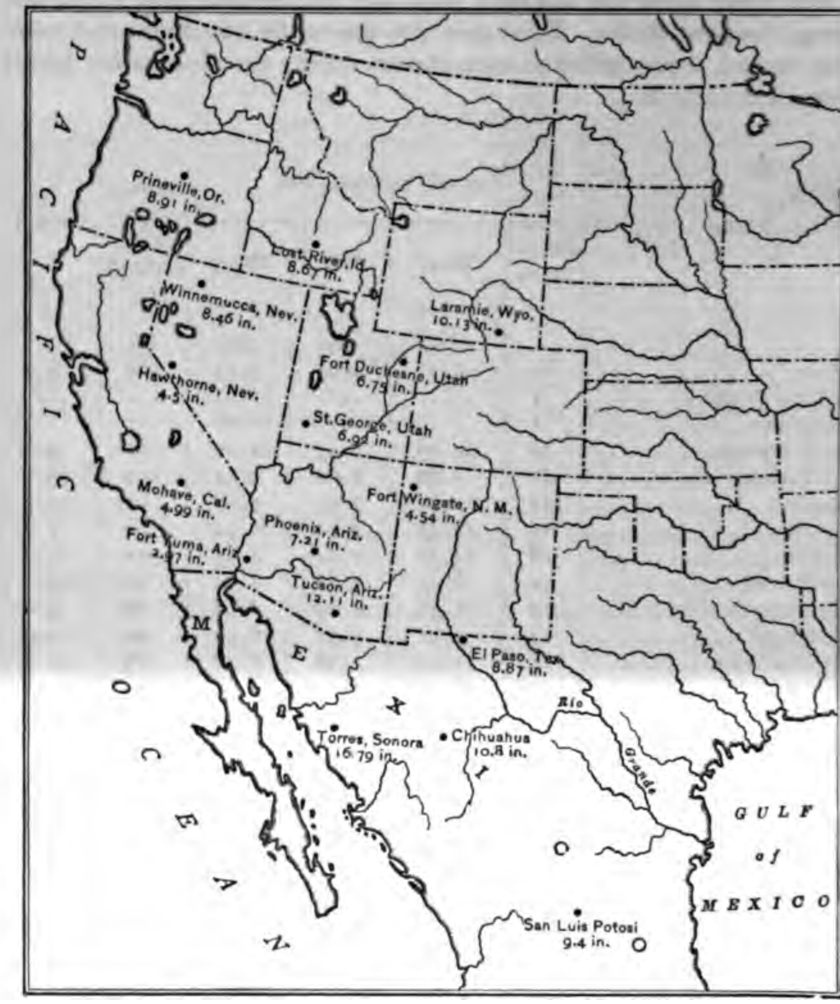


Fig. 4.—Location of and annual precipitation at certain stations in the arid region of western America. Chiefly from records of the U. S. Weather Bureau. (Reprinted from Publication No. 6.)

The arid area to the northeastward and leeward of the higher portion of the main range of peninsular California, however, can scarcely exceed this limit, although no measurements have been made. Near Bay San Felipe were seen wheel-tracks which had been made sixteen years before, while it is currently reported that the deep ruts of the gun-carriages of the

Walker Filibustering Expedition, where sheltered from the wind, are still visible in the deserts in the northern part of the peninsula after half a century.

The seasonal distribution of the rainfall in a region in which the normal precipitation bears a low ratio to evaporation may not only exert a marked influence on the character of the vegetation, but may also operate to produce desert conditions and make possible the support of xerophytic vegetation only, in districts with a large amount of rainfall. Thus, if the greater part of the precipitation should occur during a season of low temperature or in the quiescent period of the native species, the resulting dryness of the growing season would result in desert conditions. Such effects are most marked in regions in which the surface layers of the substratum consist of loose material not capable of retaining water in sufficient quantity for moisture-loving species. A striking example of this feature is offered by the area around Crater Lake, Oregon, as described by Coville. The surface layers in this locality consist of powdered pumice apparently almost devoid of humus, from which water drains with extreme rapidity. Snowfall to a depth of about 10 feet occurs in winter, but after this melts the soil becomes extremely dry and the plants capable of enduring the resulting drought show marked protective adaptations, the vegetation consisting principally of such species as *Phlox douglasii*, *Spraguea umbellata*, and *Arenaria pumicola*.*

The above factors must be taken into account in the interpretation of alpine districts in many parts of the world. The precipitation on mountain summits is very great, but in some instances it is in the form of snow, which melts and drains away very rapidly, leaving the humus-free soil extremely dry, while the air shows rapid alterations from high to extremely low relative humidity. An example of this character is offered by the summit of Agassiz Peak in the San Francisco Mountains of northern Arizona. A description of the meteorological conditions on this mountain will be found on pages 79 and 80.

SOIL.

The chief factor in the production of deserts is a lack of water as a nutrient substance for vegetation. Deserts may be produced as a result of other defective nutritive and mechanical conditions as well. Such conditions are to be found in areas in which the soil contains harmful substances in injurious concentration in the soil, of which the alkali lands are familiar examples. Sterile areas, due to lack of nutritive material and water and to the unsuitable mechanical conditions of the soil, are offered by stretches of sand-dunes and plains in many parts of the world. In

*F. V. Coville. The home of *Botrychium pumicola*. Bulletin Torrey Botanical Club, 1901, vol. 28, p. 109. The August vegetation of Mount Mazama, Oregon. Mazama, 1896, vol. 1, p. 170.

sand-dunes the substratum is in constant motion of greater or less rapidity, lacks a suitable water-supply, and may be devoid of other nutritive material. Even if the dune areas are supplied with water in proper quantities, the peculiar character and movements of the substratum result in some striking forms of vegetation.

A combination of the above mechanical and physical conditions of the soil and of the presence of harmful substances is offered by the white sands in the Otero basin in New Mexico, of which a more detailed description is given on pages 11 to 15.

The sand-dunes in this district consist chiefly of gypsum, the principal remaining constituents being silicates and calcium chloride in the proportions of 3 per cent and 1 per cent respectively. The gypsum is slowly soluble in cold water and retains the greater part of the water which falls upon it. Consequently the dunes are really moist hillocks of a granular structure, the surface layers of which are dried out by the heat of the sun to a depth of a few inches. The dried layer is constantly drifted by the wind, and the exposed layers are dried in turn, so that the progressive action of sand-dunes is manifested. The underlying layers at some depth often become solidified and stratified, but are easily broken up when exposed to the action of the sun and wind. The moisture included is sufficient for a number of species of plants, but the mineral substances in solution make it possible for only those forms which are adapted to an alkaline substratum to gain a foothold. The White Sands absorb the entire precipitation and give rise to no distinct streams, but occasional small pools or tanks of water highly charged with calcium salts are to be found in areas among the dunes. In western Australia extensive areas of gypsum desert are to be found which, it is reported, form a distinct harder surface crust instead of a granular layer, as in the instance described above, but no exact analyses of the substratum are at hand.

A number of districts in America show inclosed pockets or basins, forming the extreme lower depressions of ancient lake and river beds, in which the soil is highly charged with salts, the most of which is sodium chloride. Examples of this character are offered by the region around Great Salt Lake, Utah, and by the Salton District in the Colorado Desert of southern California. The characteristic vegetation in both instances is composed of species showing halophytic adaptations resembling those found near the seashore.

Limited areas in various regions show soils impregnated with sodium sulphate, sodium carbonate, potassium sulphate, sodium phosphate, sodium nitrate, calcium sulphate, calcium chloride, magnesium chloride, and magnesium sulphate. In agricultural operations two types of such soils are recognized, namely, *white alkali* and *black alkali*.

The nature of the mixture in the soil constituting white alkali is illustrated by the following analysis:

*Surface Crust of Soil from Kern Island, Bakersfield, California.**

	P. ct.		P. ct.
Potassium sulphate	0.52	Calcium phosphate	0.20
Sodium sulphate	82.96	Calcium carbonate	.10
Sodium chloride	.48	Ferric and aluminum oxides	.30
Sodium carbonate	.40	Silica	1.34
Magnesium sulphate	.50	Organic matter and water of crystallization	4.07
Magnesium carbonate	.13		

Alkali from the Valley of the Rio Grande in New Mexico.†

	No. 1.	No. 2.	No. 3.
	P. ct.	P. ct.	P. ct.
Insoluble matter	75.59	74.24	34.40
Portion soluble in water	24.41	25.76	65.60
Composition of soluble portion:			
Potassium oxide	4.71	3.57	.21
Sodium oxide	37.72	28.97	31.38
Calcium oxide	5.57	6.60	7.92
Magnesium oxide	.98	1.55	1.05
Aluminum	3.24	0.00	0.00
Sulphates	10.16	47.72	52.67
Chlorides	47.96	4.58	1.20
Carbonates	trace	trace	trace
Water of crystallization and organic matter	.44	8.04	5.84

The composition of the impregnating salts producing the black alkali s shown by the following analysis of alkali salts from soil near Fresno, California.‡

	P. ct.		P. ct.
Potassium chloride	1.30	Sodium carbonate	18.72
Sodium sulphate	18.23	Sodium bicarbonate	25.72
Sodium chloride	35.93	Phosphoric acid	.10

*Analysis by E. W. Hilgard: Report of Work of the Agricultural Experiment Stations for the year 1900, p. 97.

† Analysis by Goss and Griffin made from three samples from different localities. Bulletin No. 22, New Mexico Agricultural Experiment Station, p. 26, March, 1897.

‡Means, T. H., and Holmes, J. G.: Soil survey around Fresno, California. Field Operations of the Division of Soils, U. S. Department of Agriculture. Second Report, p. 373, 1900.

HISTORICAL.

The current conceptions of deserts are neither adequate nor correct, if the descriptions in the best dictionaries and cyclopedias are to be taken as an index. A work of wide circulation and use defines a desert as "A region that is wholly or approximately without vegetation. Such regions are rainless, usually sandy, and commonly not habitable." Another characterizes a desert as "A region of considerable extent which is almost if not quite destitute of vegetation, and hence uninhabited, chiefly on account of an insufficient supply of rain; as the Desert of Sahara; the Great American Desert. The presence of large quantities of movable sand on the surface adds to the desert character of a region. The word is chiefly and almost exclusively used with reference to certain regions in Arabia and northern Africa and others lying in central Asia. The only region in North America to which the term is applied is the Great American Desert, a tract of country south and west of the Great Salt Lake, once occupied by the waters of that lake when they extended over a much larger area than they now occupy. The name *Great American Desert* was originally given to the unexplored region lying beyond the Mississippi without any special designation of its limits" (fig. 6).

The insufficiency of the above descriptions obviously rests upon faulty observations and upon the failure to recognize the fact that the habitability of a region is no criterion of its arid character. The development of modern methods of transportation has made possible the maintenance of dwellings and towns with a considerable population at 100 or even 200 miles from the nearest supply of water. Also such facilities are not necessary to the sustenance of a population in deserts of the most extreme type as illustrated by the Sahara, which has a population of 2,500,000 people. So far as the vegetation is concerned, the actual number of individuals is much less than on a similar area in a moist climate; this in fact is one of the chief characteristics of a desert, but it would not be safe to estimate the total number of species much below the average number.

Lastly, be it remembered that local topography has but little influence on the desert character of a region. Sandy flats, plains, valleys, and rocky hills reaching to such altitudes as to become mountains are included in some desert tracts. It follows, as a natural consequence of the sparse vegetation as one factor, that the surface layers of the substratum, being usually dry in arid regions, are readily shifted and worn by winds.

The designation of the vast region between the Missouri River and the Rocky Mountains as the Great American Desert rested upon a lack of definite knowledge by the earlier geographers, which was shown by textbooks as recently as 1843. Later, when the more exact results of the earlier explorations and surveys became known, the more important arid regions were fairly well delimited, and the desert areas in the Bad

Lands, the Staked Plains of Texas, the Chihuahua Desert, the Great Basin, and the Colorado Desert were shown approximately within the districts which may appropriately be designated as desert at the present

FIG. 5.—Western America, showing conceptions of American deserts current in 1835. Copied from T. G. Bradford's Comprehensive Atlas, published at Boston in 1835. (Reprinted from Publication No. 6.)

time. This conception of the matter is shown in fig. 6, being a map from a text-book on physical geography published in 1859.

A study of the physiographic, floristic, and meteorological features of western North America has resulted in delimiting two great desert areas

by the geographer, botanist, and meteorologist. The outlines of these might be roughly traced by lines inclosing the stations shown in fig. 4. These regions may be designated as the Sonora-Nevada Desert and the Chihuahua Desert.

The Sonora-Nevada Desert embraces portions of Utah, Idaho, Washington, Oregon, Nevada, California, Arizona, Baja California, Sonora, and Sinaloa. The northern portion of this region is mainly comprised in the Great Basin and embraces the beds of a number of ancient lakes and the surviving Great Salt Lake. Other special physiographic features of interest in this connection are the areas which bear the names of Snake River Desert of Idaho; the Sage Plains of Washington; the Lava Beds of Oregon; the Ralston Desert in Nevada; Death Valley, Mohave Desert, Colorado Desert, Salton Desert in southern California and Arizona; the Painted Desert in Arizona and New Mexico; and the Sonora Desert in Mexico. The southern portion of the region consists of a series of extended slopes and terraces traversed by many ranges of hills and mountains with peaks of some altitude. Along the shores of the Gulf of California and of the Pacific Ocean proper the desert area includes the entire surface to within a few feet of the water's edge, and the xerophytic vegetation of the plains comes into direct contact with the mangrove and strand flora.

The Chihuahua Desert occupies the central table-land of Mexico east of the Sierra Madre, extending as far south as San Luis Potosi and including parts of the States of Coahuila, Chihuahua, and Texas and also portions of Arizona and New Mexico. The Bad Lands of the Dakotas and Montana and the Red Desert of Wyoming, both included in the "Great American Desert" (fig. 6), might be regarded as a northern arm of this region for the purposes of this paper. The arid portions of this area consist for the most part of great valleys inclosed by parallel ranges of mountains which in some instances attain such altitudes as to be timber-clad and even bear an alpine vegetation.

FORMATION AND EXTENT OF DESERTS.

The deserts of the world's surface are not easily delimited, even in North America, where some attention has been given to the geographical extent and position of the arid areas, which may be taken to cover over 500,000 square miles. The accompanying map (plate 61) indicates the general location of deserts only and not an outline of the areas to be included. So far as estimates may be based upon the data obtained from it, a very large proportion of the earth's surface receives a rainfall much less than the possible evaporation, and is therefore inhabited by plants of specialized form and of xerophytic and halophytic adaptations.

These desert areas have been subject to many conditions of change in recent geological history, as a result of which some are more arid now than ever before in their history, while in other cases the weight of evidence lies

in favor of the view that the present is a state of maximum aridity, which may become still more accentuated. Small areas may become suitable to desert types of vegetation by highly localized causes, such as an accumulation of salts brought to the surface by the capillary action of introduced water.

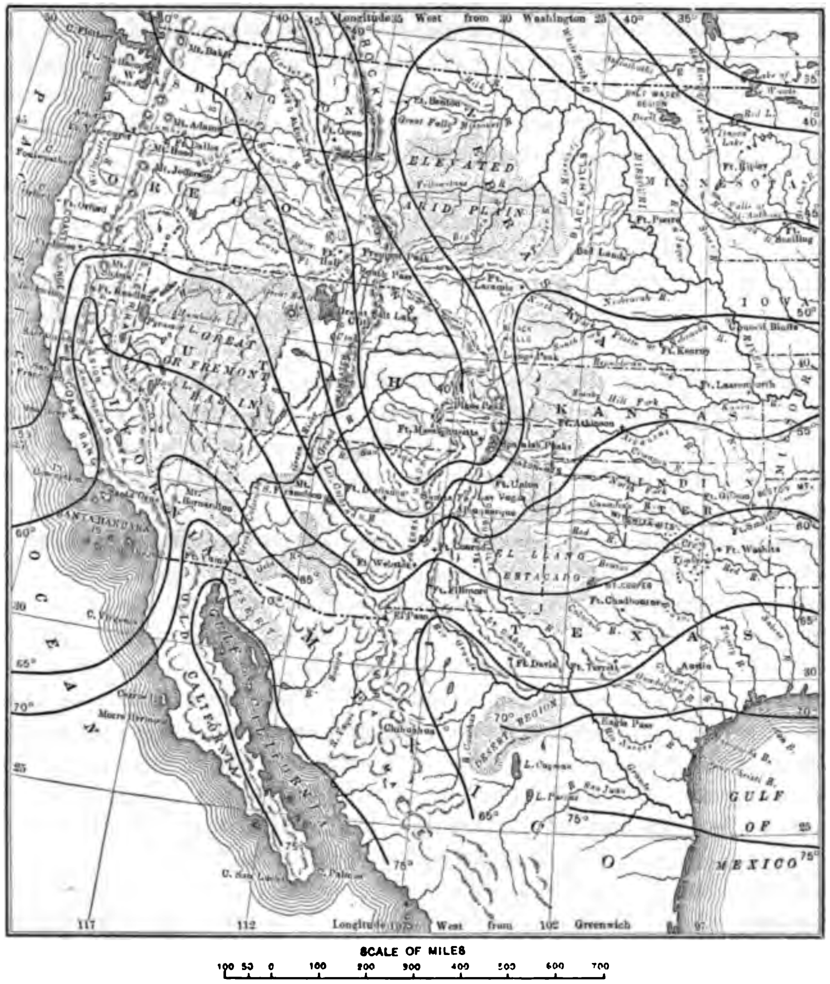


FIG. 6.—Western America, showing conceptions of American deserts current in 1859. Copied from Warren's Physical Geography, published in 1859. (Reprinted from Publication No. 6.)

The chief cause of deserts, however, may be ascribed to the change from lower temperatures and accompanying greater supply of moisture in glacial times to the comparative aridity of the present. This change, however, may not be assumed to have been one constantly moving in the same

direction. According to Russell (I. C. Russell, Geological History of Lake Lahontan, Monograph 11, U. S. Geological Survey, 1886), the Great Basin region of Nevada underwent a period of desiccation before it received the waters of Lake Lahontan, which, after reaching a maximum height without overflowing, receded to leave the region even more completely desert than at the present time. The next oscillation toward increase of the water-supply carried the lake back to a level higher than the first, and then receded to leave a desert for the third time, which, so far as weight may be given to some of the evidence, reached its greatest aridity a few hundred years ago; so that the Nevada desert is now not so dry as it has been within the period witnessing the advent of man.

Climatological and geological changes of this kind work a double effect upon a region. The decreasing rainfall results in a general aridity of the entire region affected, and the reduction of the streams is followed by a recession of lakes and other sheets of water by which basins with the soil highly charged with salts are left to specialized types of vegetation. Comparatively local causes, such as the cutting off of the head of the Gulf of California by the silt of the Colorado River, may leave a basin to become a part of the contiguous desert, as is also the case with the Pattie Basin to the southward. Changes of level by both upheaval and subsidence may also contribute to the formation and extension of deserts, as indicated in a preceding section.

The great Lake Eyre basin in southern central Australia is taken by some geologists to have had a complicated history, by which the region in which it was included was slowly depressed until flooded by the sea, then emerged to undergo the resultant changes in the muds that covered its floor. In a second subsidence the surface was carried down to a level where its floor was 39 feet below sea-level. Two rivers carried such volume of water into it that it became the bed of a fresh-water lake, with a luxuriant development of plant and animal life which found agreeable conditions for existence. The entrance from the sea appears to have become filled, the amount of river flow decreased, the annual evaporation in the basin being about 86 or 88 inches per year, and a desiccation set in probably early in the Pleistocene, which continued to the present time, although, as in all deserts, small bodies of water occasionally collect in the lower parts of the basin. (J. W. Gregory, The Dead Heart of Australia, London, 1906.)

Lastly, many writers hold to the opinion that distinct changes in climate with increasing aridity have taken place on various parts of the earth's surface long since the advent of man and well within historic time. The most pronounced of such views is held by Huntington concerning central Asia. He says:

> To sum up the history of Lop-Nor during the last 2,000 years: We have first a comparatively large lake, said to measure 75 miles each way, in spite of the fact that the populous towns of Lulan and of more remote regions diverted much more water than now. Next, during the early centuries of the Christian era, there is

a decrease in the recorded size of the lake, even though the towns of Lulan were being abandoned and their water was being set free to reinforce the lake. Then, in the Middle Ages, there was an expansion of the lake, which can not have been due to diminished use of the rivers for irrigation, for the population of the Lop Basin at that time was greater than now, though not equal to that of the flourishing Buddhist times, a thousand or more years earlier. Finally, during the last few hundred years there has been a decrease both in the size of the lake and the population about it. If Lop-Nor alone is considered, this sequence of events is not proved by compulsory evidence in all particulars; but it fits the facts better than any other theory as yet suggested. And, more than this, it agrees with all the data which I gathered from the whole of the 1,500 miles of longitude and 400 of latitude of the Lop basin and from Kashmir. All the facts are explicable on the theory of a secular change of climate from moister to drier conditions, with a rapid intensification in the early part of the Christian era and a slight reversal in the Middle Ages.*

Hedin, who has carried on extensive explorations, holds views quite different from those of Huntington and sees no evidence of climatic change in the extensive disturbances of the population and pursuits of the inhabitants which he notes.

Evidence upon a matter of this kind is not easily sifted, and a spirit of controversy prevails in most of the writings upon the subject. The short-period oscillations of climate, which swing back and forward with average amplitude; the movements of nomads and half-civilized people in response to these changes, and the abandonment of schemes for division and use of water for agricultural purposes, may in some instances give remains simulating the effects of increasing desiccation. Exact meteorological observations extend over so brief a period that they throw no light on the main question. (See R. DeC. Ward, Changes in Climate, *Popular Science Monthly*, 1906, vol. 69, p. 458.) Much has been written upon the subject by explorers and investigators of archeological remains in the deserts of northern and southern Africa. A review of these writings would be out of place in the present volume.

INFLUENCE OF THE DESERT ON LIFE.

The geological and climatic changes by which a region varies from a cool, moist, equable climate, with well-leached soils and complete drainage, to an arid basin, with saline or alkaline soils, imperfect drainage, great evaporation, and wide diurnal and annual changes in temperature, entail, of course, sweeping modifications in the composition of the flora, and consequently the fauna. Such movements would put vegetation in a state of continued high stress. Forms in existence at any given time would gradually perish as their habitats were narrowed and the limits of their power of accommodation and acclimatization were reached. New forms which arose by a supposed gradual modification and selection

*E. Huntington: The Rivers of Chinese Turkestan and the Desiccation of Asia. *Geographical Journal*, October 28, 1906, p. 352; and Lop-Nor, A Chinese Lake, Bulletin American Geographical Society, February and March, 1907; see p. 146.

would take up the succession, the process of adaptation continuing until the present succulent and spinose types were reached. On the other hand, the new conditions might be met by sports or mutants, offsprings of the existing forms, which diverged from the parental types very widely, and which occur in such manner that some would be born which would be able to survive and thrive under the modified conditions of soil and climate. Gradual modifications by which a long series of forms, each slightly different from its immediate progenitors, appear to have been found among animals, but with plants no such series has yet been brought to light. These organisms, on the contrary, exhibit sports or saltatory derivatives, which now have been seen and recognized in a number of species. Such mutants are now occurring and we may predicate with certainty that they have occurred with normal frequency during the formation of the deserts of southwestern America. That many of them have survived to become constituents of the present flora is a supposition fully in accord with the facts, and it seems reasonable to assume that the greater number of the units of the plant population have arisen in this manner.

The recession of an inland sea or the drying up of a lake might lay bare great areas in regions of relatively small precipitation, with the result that the desert would be extended. Such new desert basin would be populated with plants by invading movements from the contiguous territory. If the adjoining areas were of equal aridity, the occupation of the new desert would be a comparatively simple matter in the succession of formations which would follow the receding waters, although a series of this kind has never been actually observed. The occupation of such a desert might, however, require great departures from the types of vegetation accessible to it, and in such instances we are confronted with the choice between possible modifications as direct adaptations to the newly presented environmental conditions or to fitting mutations. The time requirement would favor the latter in most instances, and there is yet no evidence at hand to prove the direct response of plants to any given environment by structural adaptations which would be suitable to that environment. Thus the armature of desert plants is often thoughtlessly cited as an adaptation by which these forms protect themselves against the ravages of animals. The presence of spines undoubtedly operates to prevent a plant from being eaten by animals, but the action of the animals has in no wise induced their formation by the plant. As a matter of fact, the fatality among desert plants by injury from animals is greatest in the seedling stage. For every prickly-pear that survives, tens of thousands of seedlings are eaten by rodents, and these seedlings are as unarmed as those of any other type. The natural selection actually operative in such cases is one that chooses among forms offered, but does not in any sense exercise a directing or guiding action on the development of such forms.

It is not to be assumed, however, that external factors are without effect upon the evolution of living things. It has not yet been demonstrated that climatic or soil factors acting upon the somatic or vegetative part of the plant produce changes that are heritable, but on the other hand, MacDougal has shown that certain external agents, when brought to bear directly upon the germ plasm of the pollen tube or the embryo-sac of a plant, may produce profound alterations which are strictly inheritable after being tested to the third generation of the progeny Solutions of zinc, calcium, and other substances combined were used and similar results followed the exposure to the action of radium.

If we seek a like possible intervention of external forces which would act upon the plant unaided by man, we might find such influence coming from radio-active substances, such as spring and rain-water, or from the effects of sulphurous and other gases, which are being set free in numberless localities, or the protoplasts most nearly in contact with the egg apparatus may well excrete substances which would produce the same effect without regard to the forces which originally caused the disturbances in the extra-ovular tissue. The actual technique of injection would be imitated in a measure by the action of foreign pollen which might find lodgment on the stigmatic surfaces and, sending down tubes through the style, introduce unusual substances into the vicinity of the egg-cell without participating in normal fertilization, which would ensue in the customary manner. Lastly it is to be said that it would appear that a most prolific source of such disturbances might be expected to result from the stings and lacerations of insects or the action of parasitic fungi, both sources of the most profound morphogenic alterations in somatic tissues, profusely exemplified by the well-known gall-formation of plants. (MacDougal, "Heredity and Origin of Species," reprinted in advance from the *Monist* for January, 1906, and distributed December 18, 1905; also "Discontinuous Variation in Pedigree Cultures," *Popular Science Monthly*, September, 1906.)

Tower (An Investigation in Evolution of Chrysomelid Beetles of the Genus Leptinotarsa, Carnegie Institution of Washington Publication 48, 1906), after eleven years of assiduous experimentation with beetles, likewise concludes that influences merely exerted upon the body are without lasting effect in the history of a race and that they are not inheritable. When such variations in moisture and temperature as would affect the germ-cells were brought to bear, however, profound changes ensued, which might be transmitted from generation to generation and which were not in the nature of adaptations.

Formerly the desert was held to be an uninhabitable place, but by the aid of the devices of modern civilization the requirements of life, comfort, and luxury may be transported to the most remote deserts, and large populations may carry on pursuits, such as mining, unconnected with

the climate, regardless of aridity. One of the most important developments of modern agriculture is that of dry farming, in which forms of economic plants are sought which will produce crops under arid conditions, and constant and assiduous attention is being given to the development of cultural methods which will facilitate the growth of plants in deserts and conserve the soil moisture by checking evaporation. These and other individual adaptations of the human animal are of extreme interest, particularly when considered by the archeologist engaged in the study of the ancient civilization of desert peoples. (C. S. Scofield, Dry Farming in the Great Basin, Bulletin No. 103, Bureau of Plant Industry, U. S. Department of Agriculture, Washington, 1907.)

One of the most difficult problems to solve is that of transportation in the desert, and there are extensive areas in American deserts that have not yet been systematically explored by reason of this condition.

The camel is perhaps the most extensively used of any means of transportation, and as such he has played an important part in the history of the human race in the arid regions of Asia and Africa. This animal has also come to be of great usefulness in Australia, where it was introduced in 1846, and a later importation of these animals, brought in 1860, accompanied the Burke and Wills Expedition across the continent. In this same period efforts were made to make use of the camel in American deserts, and although the conditions were undoubtedly and still seem quite as favorable, the movement was a failure by reason of prejudice, and of the organization of transport of burros, horses, and mules already in a high state of specialization in this region. The extension of railways to tap mining regions and the usefulness of the modern motor car, as proved in the deserts of Nevada, now make any further consideration of the camel unnecessary along main lines of travel, while the solitary traveler or the small party following personal routes have available animals and supplies, so that the most economical outfit is that of horses, mules, and burros. A camel is reputed to be able to carry a load of 600 pounds with ease, but the same amount might be taken by three or four burros at a cost of original investment and maintenance only a fraction of that of the camel-train. It is to be said, however, that a small efficient camel-train would make possible the scientific exploration of the deserts of western Sonora and of the region traversed by the Camino del Diablo with some certainty of success.

A comprehension of the part that water plays in existence and travel in the desert is to be gained only by experience. Some of the native animals, such as mice and other small rodents, have been known to live on hard seeds without green food for periods of several months, or even as long as two or three years, and nothing in their behavior indicated that they ever took liquid in any form. (F. V. Coville, Desert Plants as a Source of Drinking Water, Smithsonian Reports for 1903, pp. 499–505. 1904.)

Crushing the pulp of a decapitated bisnaga (*Echinocactus*) to obtain a drink in Central Arizona.

Papago Indian drinking from a cactus (*Echinocactus emoryi*) west of Torres, Mexico.

Deer and peccary are abundant in deserts in Sonora in which the only available supply of open water is to be found in the cacti. The endurance of the camel is well known, and some of the best authenticated evidence upon the matter comes from Australia. The camels of the Tietkins party in 1891 and 1892 made a march of 537 miles in 34 days without a drink. These animals take water every day when a supply is available, but it is their capacity for accommodation that has made them such a potent factor in transportation in the deserts of Asia, Africa, and Australia. Other animals, including the common domestic sheep, are also capable of making such changes in their habits that they may go for weeks without a drink.

Man and his most constant companion on the desert in America, the horse, are comparatively poorly equipped against the rigors of the desert. A horseman may go from the morning of one day until some hour of the next in midsummer and neither he nor his horse will incur serious danger: experiences of this kind are numerous. If the traveler is afoot, abstinence from water from sunrise to sunset is a serious inconvenience to him, and if he continues his journey, the following morning his sufferings may so disturb his mental balance that he may be unable to follow a trail, and by the evening of that day, if he has not come to something drinkable, he may not recognize the friendly stream in his way; instances are not unknown in which sufferers from thirst have forded streams waist deep to wander out on the dry plain to a grisly death.

Some estimate may be made of the actual amount necessary from the fact that a worker at the Desert Laboratory during the course of an ordinary day in May, at Tucson, consumed 16 pints of water. A horse would have used 15 or 20 gallons in the same time. A walk of 3 or 4 miles was taken, but no special muscular effort beyond this was involved. A march across the desert in midsummer would increase this quantity by half. Under such circumstances, a canteen of less capacity than a gallon is a toy, and one of real usefulness should contain at least twice that amount. The most notable example of endurance of thirst is that of a Mexican prospector hunting for a "lost mine" near the old Camino del Diablo, or trail from Sonora to Yuma, who made camp safely after being out for eight days with a supply sufficient for one. This experience is not likely to be duplicated soon, although it is reported that Indians often go as long as four days without water. (W J McGee, Desert Thirst as a Disease, Interstate Medical Journal, 1906, vol. 13, No. 3, 1906.)

The experience of the field expeditions from the Desert Laboratory demonstrates that saline or alkaline waters which contain as much as one-fourth of 1 per cent of salts may be used for periods of many days without serious discomfort, but if the proportion be increased to one-third of 1 per cent only hardened travelers may use it, while water which contains as much as one-half of 1 per cent is inimical to health and comfort,

although it might suffice for a few hours or save the life of a person who had been wholly without water.

All devices for allaying the discomfort arising from the dryness of the mucous membrane, such as carrying bullets or pebbles in the mouth, chewing grass or a piece of rubber, are wholly futile in meeting the serious thirst problem. The relative humidity often falls to 5 per cent in the Southwestern deserts, and in a temperature of over 100° the evaporation from a vessel of water standing in the open may be as much as an inch a day. The amount thrown off by the skin is correspondingly great, and if the loss is not made good, thirst ensues, and ten hours' lack of water may thicken the tongue so that speech is impossible.

The Indian and the desert traveler often seek relief in the juices of plants when water fails. The fruits of some of the prickly-pears are slightly juicy, the stems of the same plant or the great trunks of the sahuaro contain much sap, but for the most part it is bitter, and while it would save life, in extremity, yet it is very unpleasant to use. The barrel-cactus, or bisnaga (*Echinocactus*), however, contains within its great spiny cylinders a fair substitute for good water. To get at this easily one must be armed with a stout knife or an ax with which to decapitate the plant, which is done by cutting away a section from the top. Lacking a suitable tool the thirsty traveler may burn the spines from the outside of the bisnaga by applying a lighted match and then crush the top with a heavy stone. This or other means is taken to remove a section 6 to 8 inches in thickness and expose the older parenchyma around the small central woody cylinder. Next a green stake is obtained from some shrub or tree that is free from bitter substances, and with this or with the ax the white tissue of the interior is pounded to a pulp and a cavity that would hold two gallons is formed. Squeezing the pulp between the hands into this cavity will give from 3 to 6 pints of a drinkable liquid that is far from unpleasant and is generally a few degrees cooler than the air (plate 62). Scouting Indians have long used the bisnaga, and a drink may be obtained in this manner by a skilled operator in 5 to 10 minutes. Some travelers are inclined to look with much disfavor on the liquid obtained in this manner, but it has been used without discomfort by members of expeditions from the Desert Laboratory. That it is often preferred by Indians to fair water is evinced by the fact that the Whipple Expedition found the Mohaves near the mouth of the Bill Williams River, in 1853, cooking ducks and other birds in the juice of these plants by means of heated stones dropped into the cavity containing the pulp.

The sap of the sahuaro (*Cereus giganteus*) and of other cacti contains bitter substances that make it impossible to be used to allay thirst by man, although it may be given to burros. A supply is usually obtained by felling the heavy trunk and elevating the ends a few inches above the ground, while the middle is allowed to sag lower over a bucket or vessel

that has been suitably placed in a hole in the ground below. A cut is made above the bucket to allow the liquid to exude, while the process is hastened somewhat by building a fire under the ends.

The experiences of the expeditions from the Desert Laboratory made it evident that a still or condenser by which even a small quantity of drinkable water could be obtained from the abundant sap of these plants or from alkaline waters would greatly facilitate field-work. After some experimentation the form adopted was one designed by Mr. Godfrey Sykes, in which the cactus pulp or liquid to be distilled was placed in a boiler of pressed steel. This boiler has a capacity of about 2 gallons and is built up of two pressed-steel kettles, one of which is inverted over the other and fastened by a riveted seam. An opening 4 inches in diameter in the bottom of the inverted vessel received a threaded fitting to which is attached a half-inch pipe with an elbow. Sections of pipe 30 inches long with conical friction joints are carried, and as many are fitted as may be necessary to secure condensation. This apparatus may be set up anywhere, and the cooling of the steam escaping through the condensing pipe may be effected in the air, by embedding in the earth, or by a drip from cloths. A capacity of several gallons per day has been shown by this apparatus, an amount that would enable a party to make a stay at a locality in which the untreated water would be wholly undrinkable. This apparatus has the additional advantage that the replacement of the outlet of the boiler with a screw plug makes it a suitable vessel for carrying a supply on the march.

Some experimentation has been made for the purpose of designing a solar condenser in which the vapor coming from a water surface under the influence of the sun's rays would be condensed on a cooler shaded portion of the glass top, and the collected drops conducted to a receiver. Devices of this sort constructed of non-soluble glass are used at the Desert Laboratory to secure water of a high grade of purity for use in injection experiments with plants. These work very slowly, however, and no form of this apparatus has yet been designed that would be of any practical value in life on the desert.

[redacted] [redacted]